US011443715B2

(12) **United States Patent**
Callway et al.

(10) **Patent No.: US 11,443,715 B2**
(45) **Date of Patent: Sep. 13, 2022**

(54) **STROBE CONFIGURATION FOR ILLUMINATION OF FRAME AT DISPLAY DEVICE**

(71) Applicant: **ATI TECHNOLOGIES ULC**, Markham (CA)

(72) Inventors: **Ed Callway**, Markham (CA); **David Glen**, Markham (CA)

(73) Assignee: **ATI TECHNOLOGIES ULC**, Markham (CA)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **16/670,635**

(22) Filed: **Oct. 31, 2019**

(65) **Prior Publication Data**

US 2020/0219309 A1 Jul. 9, 2020

Related U.S. Application Data

(60) Provisional application No. 62/853,032, filed on May 26, 2019, provisional application No. 62/788,536, filed on Jan. 4, 2019.

(51) **Int. Cl.**
G06T 15/50 (2011.01)
G09G 5/10 (2006.01)
(Continued)

(52) **U.S. Cl.**
CPC ***G09G 5/10*** (2013.01); ***G06F 3/013*** (2013.01); ***G06T 15/506*** (2013.01); ***G09G 3/20*** (2013.01); ***G09G 3/3208*** (2013.01); ***G09G 3/3406*** (2013.01); *G09G 3/32* (2013.01); *G09G 3/3426* (2013.01); *G09G 3/36* (2013.01); *G09G 2310/0237* (2013.01);
(Continued)

(58) **Field of Classification Search**
None
See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

9,268,160 B2 2/2016 DeCusatis
9,325,978 B2 4/2016 DeCusatis
(Continued)

FOREIGN PATENT DOCUMENTS

CN 1684134 A 10/2005
CN 101563724 A 10/2009
(Continued)

OTHER PUBLICATIONS

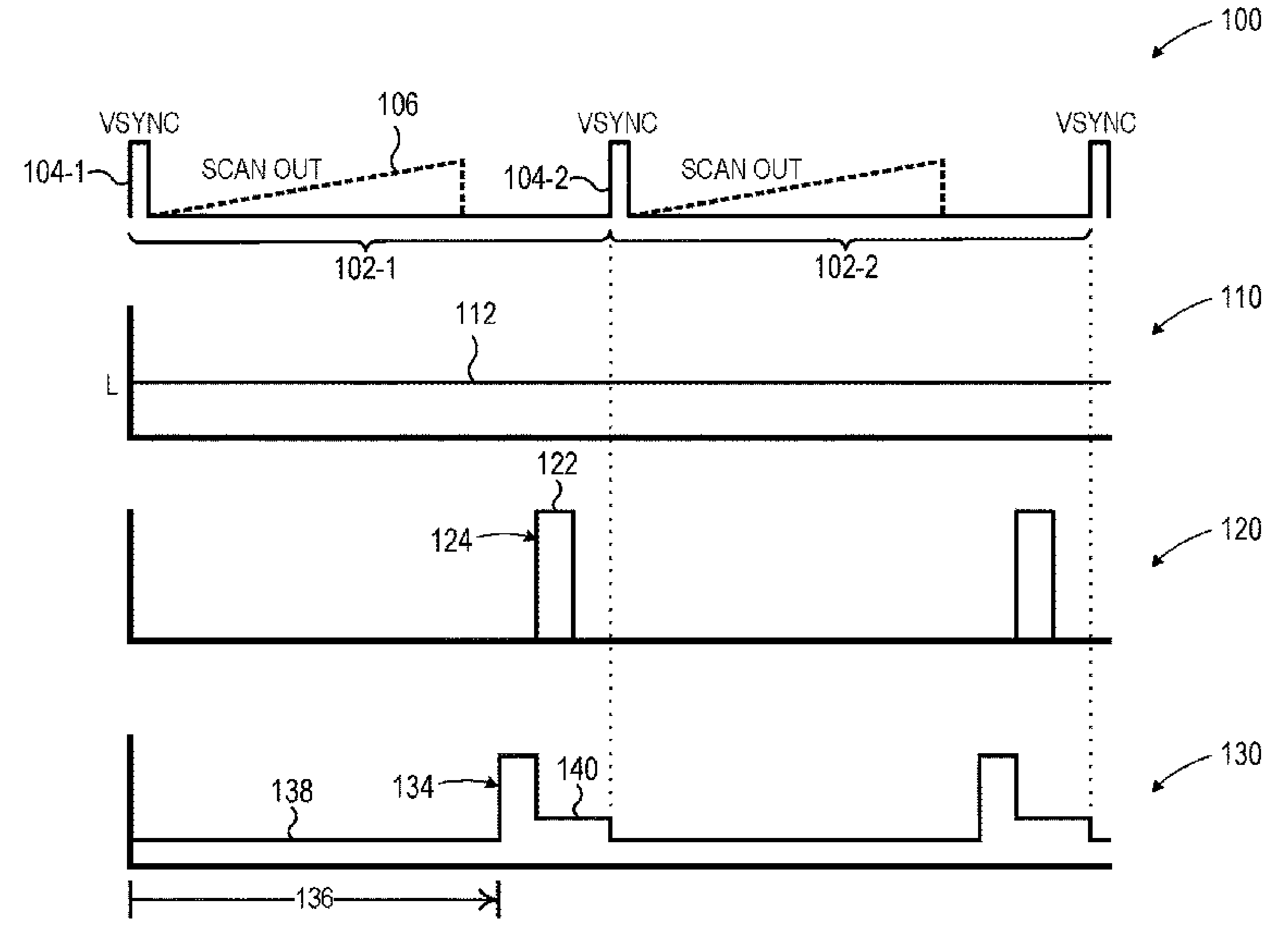
U.S. Appl. No. 16/436,876, filed Jun. 10, 2019 listing Koo, Anthony WL. as first inventor, entitled, "Frame Replay for Variable Rate Refresh Display," 42 pages.
(Continued)

Primary Examiner — Yanna Wu

(57) **ABSTRACT**

A display system includes a rendering device and a display device. The rendering device is to render a sequence of frames for display at the display device, wherein the display device is to use an illumination strobe during each frame period associated with a corresponding frame of the sequence of frames. The rendering device further is to determine a position of the illumination strobe within each frame period based one or more input parameters, each input parameter representing a corresponding operational characteristic of one of the rendering device or the display device.

20 Claims, 24 Drawing Sheets



(51) **Int. Cl.**

G09G 3/34	(2006.01)
G09G 3/3208	(2016.01)
G09G 3/20	(2006.01)
G06F 3/01	(2006.01)
G09G 3/32	(2016.01)
G09G 3/36	(2006.01)

(52) **U.S. Cl.**
CPC *G09G 2320/0247* (2013.01); *G09G 2320/0261* (2013.01); *G09G 2320/062* (2013.01); *G09G 2320/0626* (2013.01); *G09G 2320/0646* (2013.01); *G09G 2320/10* (2013.01); *G09G 2330/021* (2013.01); *G09G 2340/16* (2013.01); *G09G 2354/00* (2013.01); *G09G 2360/145* (2013.01)

(56) References Cited

U.S. PATENT DOCUMENTS

9,373,286	B2	6/2016	Ruckmongathan	
2003/0085894	A1	5/2003	Tatsumi	
2005/0259064	A1	11/2005	Sugino et al.	
2006/0050049	A1	3/2006	Lin et al.	
2009/0040374	A1	2/2009	Kobayashi	
2010/0091033	A1	4/2010	Itoyama et al.	
2012/0307161	A1	12/2012	Ishihara et al.	
2015/0109286	A1	4/2015	Verbeure et al.	
2017/0018232	A1	1/2017	Nicholson	
2017/0053620	A1*	2/2017	Law	G06T 1/20
2018/0301097	A1*	10/2018	Yoshida	G09G 3/3614
2019/0163978	A1*	5/2019	Yang	G06K 9/6262
2019/0244572	A1*	8/2019	Le	G09G 3/36
2019/0318677	A1	10/2019	Lu et al.	
2019/0373882	A1	12/2019	Zhang	
2019/0377923	A1	12/2019	Chen et al.	
2020/0160812	A1	5/2020	Tovchigrechko et al.	

FOREIGN PATENT DOCUMENTS

CN	101572076	A	11/2009
CN	102333200	A	1/2012
CN	106356036	A	1/2017

OTHER PUBLICATIONS

U.S. Appl. No. 16/889,318, filed Jun. 1, 2020 listing Lei, Jun as first inventor, entitled, "Display Cycle Control System," 44 pages.

U.S. Appl. No. 16/670,618, filed Oct. 31, 2019 listing Callway, Ed as first inventor, entitled, "Frame-Rate Based Illumination Control at Display Device," 107 pages.

U.S. Appl. No. 16/670,673, filed Oct. 31, 2019 listing Callway, Ed as first inventor, entitled, "Region-by-Region Illumination Control at Display Based on Per-Region Brightness," 109 pages.

U.S. Appl. No. 16/670,651, filed Oct. 31, 2019 listing Callway, Ed as first inventor, entitled, "Region-by-Region Illumination Control at Display Device Based on Per-Region Motion Estimation," 107 pages.

U.S. Appl. No. 16/670,664, filed Oct. 31, 2019 listing Callway, Ed as first inventor, entitled, "Foveated Illumination Control at Display Device," 106 pages.

International Search Report and Written Opinion dated Apr. 20, 2020 for International Application No. PCT/IB2019/061315, 16 pages.

Non-Final Office Action dated Aug. 6, 2020 for U.S. Appl. No. 16/670,651, 29 pages.

Non-Final Office Action dated Jul. 31, 2020 for U.S. Appl. No. 16/670,664, 28 pages.

Non-Final Office Action for U.S. Appl. No. 16/670,673 dated Mar. 30, 2021, 20 pages.

Non-Final Office Action dated Nov. 3, 2020 for U.S. Appl. No. 16/670,618, 27 pages.

Notice of Allowance dated Jan. 27, 2021 for U.S. Appl. No. 16/670,664, 26 pages.

Notice of Allowance dated Apr. 16, 2021 for U.S. Appl. No. 16/670,664, 26 pages.

Baker, Simon, et al., "Motion Blur Reduction Backlights", TFT Central, Mar. 21, 2013, 29 pages.

Day, Michael, et al., "Creating Uniform LED Intensity in RGB Billboard and Video Displays", EE|Times, Oct. 17, 2005, 5 pages.

"Combining Variable Refresh Rate and Strobed Backlight", https://display-corner.epfl.ch/index.php/Combining_variable_refresh_rate_and_strobed_backlight, accessed May 1, 2021, 3 pages.

Notice of Allowance dated Apr. 16, 2021 for U.S. Appl. No. 16/670,664, 10 pages.

Notice of Allowance dated Jun. 11, 2021 for U.S. Appl. No. 16/670,651, 8 pages.

Notice of Allowance dated May 14, 2021 for U.S. Appl. No. 16/670,618, 8 pages.

Final Office Action dated Jul. 26, 2021 for U.S. Appl. No. 16/670,673, 7 pages.

Notice of Allowance dated Apr. 20, 2022 for U.S. Appl. No. 17/464,889, 5 pages.

International Preliminary Report on Patentability dated Jul. 17, 2021 for PCT /IB2019/061315, 9 pages.

Notice of Allowance dated Mar. 8, 2022 for Chinese Application No. 201980088986.3, 6 pages.

Non-Final Office Action dated Feb. 15, 2022 for U.S. Appl. No. 16/670,673, 9 pages.

* cited by examiner

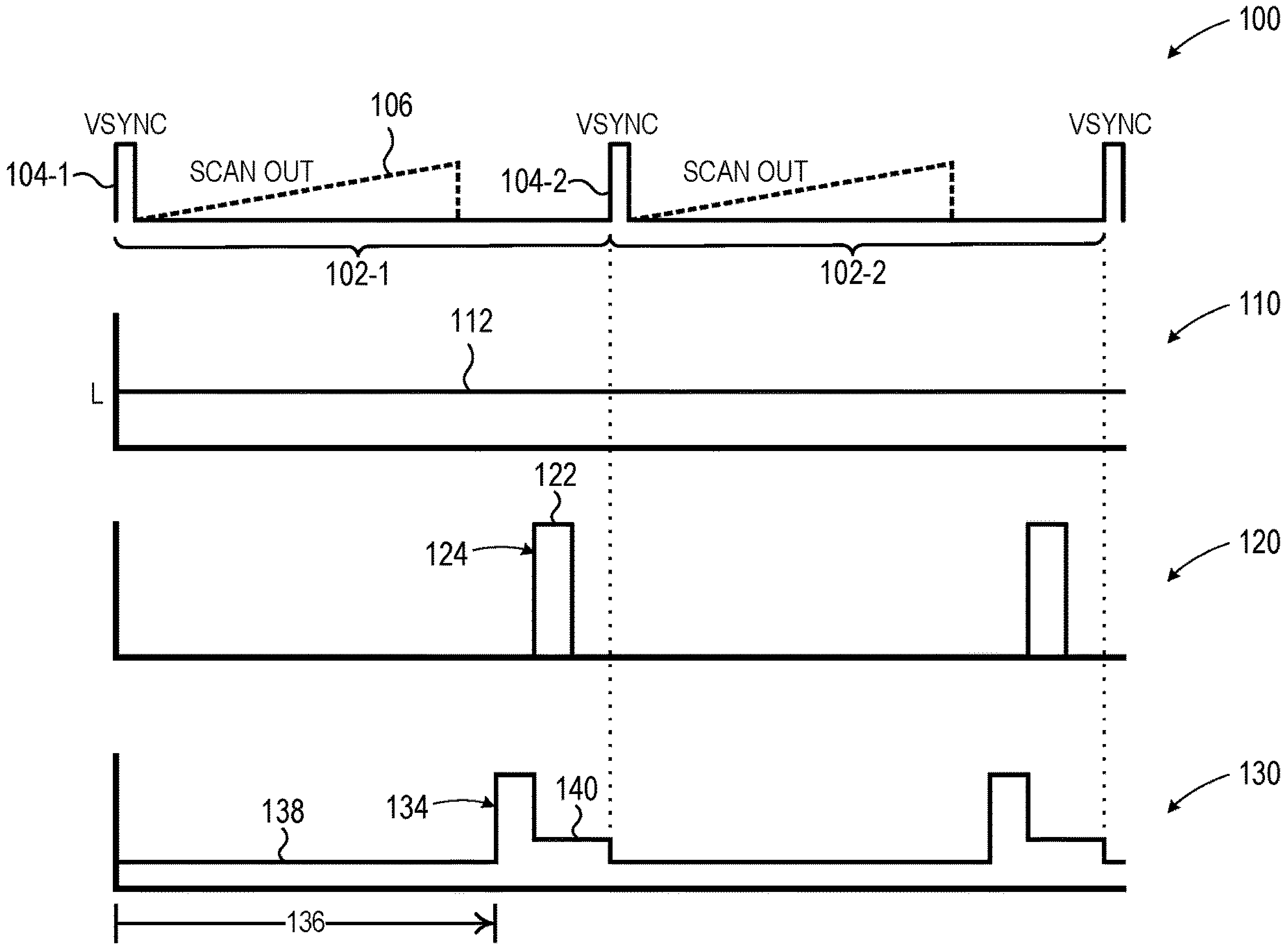

100
VSYNC
106
SCAN OUT
104-1
VSYNC
104-2
SCAN OUT
VSYNC
102-1
102-2
110
112
L
122
124
120
130
140
138
134
136

FIG. 1

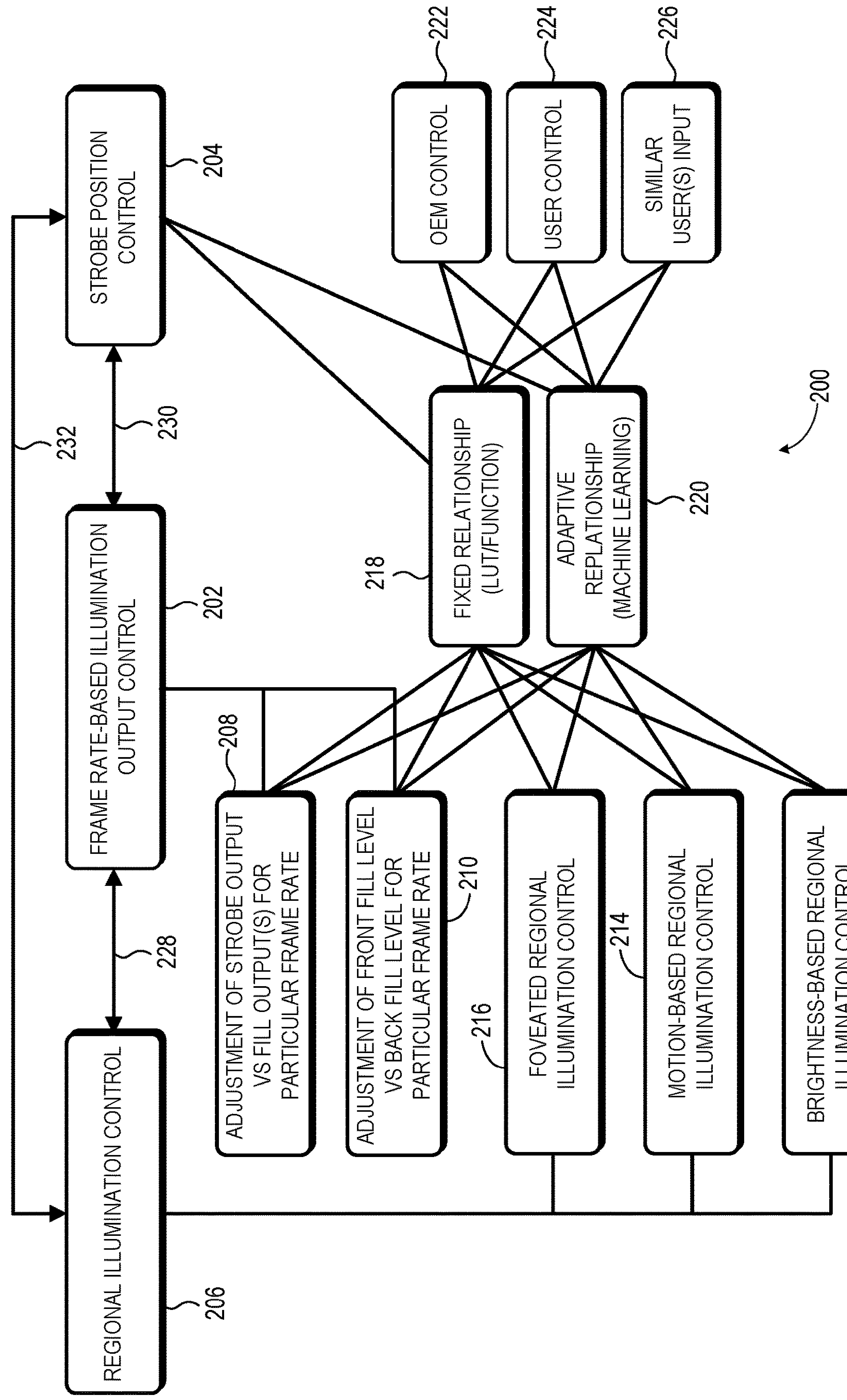

STROBE POSITION CONTROL
204
FRAME RATE-BASED ILLUMINATION OUTPUT CONTROL
202
REGIONAL ILLUMINATION CONTROL
206
232
230
228
OEM CONTROL
222
USER CONTROL
224
SIMILAR USER(S) INPUT
226
FIXED RELATIONSHIP (LUT/FUNCTION)
218
ADAPTIVE REPLATIONSHIP (MACHINE LEARNING)
220
200
ADJUSTMENT OF STROBE OUTPUT VS FILL OUTPUT(S) FOR PARTICULAR FRAME RATE
208
ADJUSTMENT OF FRONT FILL LEVEL VS BACK FILL LEVEL FOR PARTICULAR FRAME RATE
210
FOVEATED REGIONAL ILLUMINATION CONTROL
216
MOTION-BASED REGIONAL ILLUMINATION CONTROL
214
BRIGHTNESS-BASED REGIONAL ILLUMINATION CONTROL
212

FIG. 2

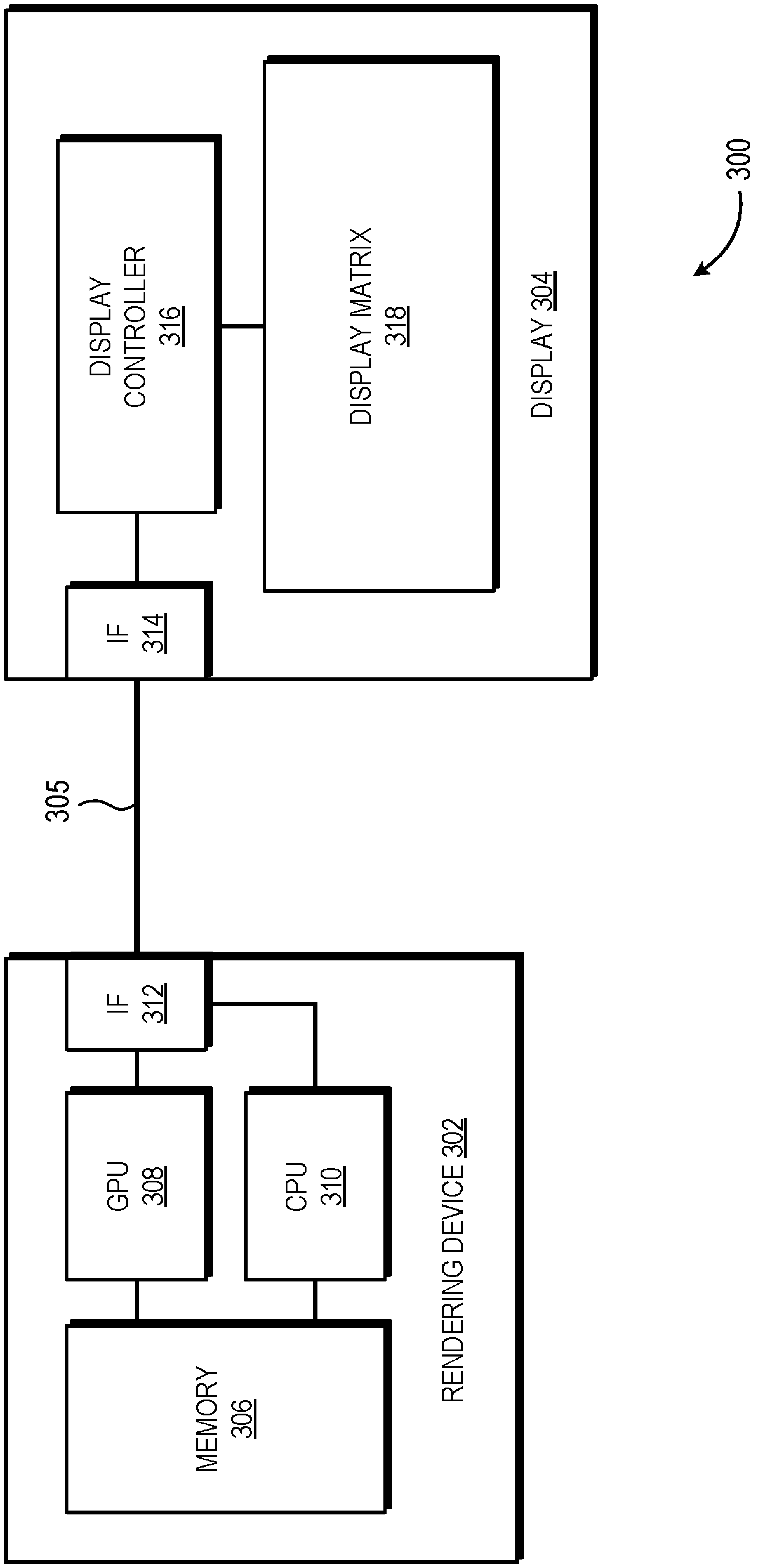

DISPLAY CONTROLLER 316
DISPLAY MATRIX 318
DISPLAY 304
300
IF 314
305
IF 312
GPU 308
CPU 310
MEMORY 306
RENDERING DEVICE 302

FIG. 3

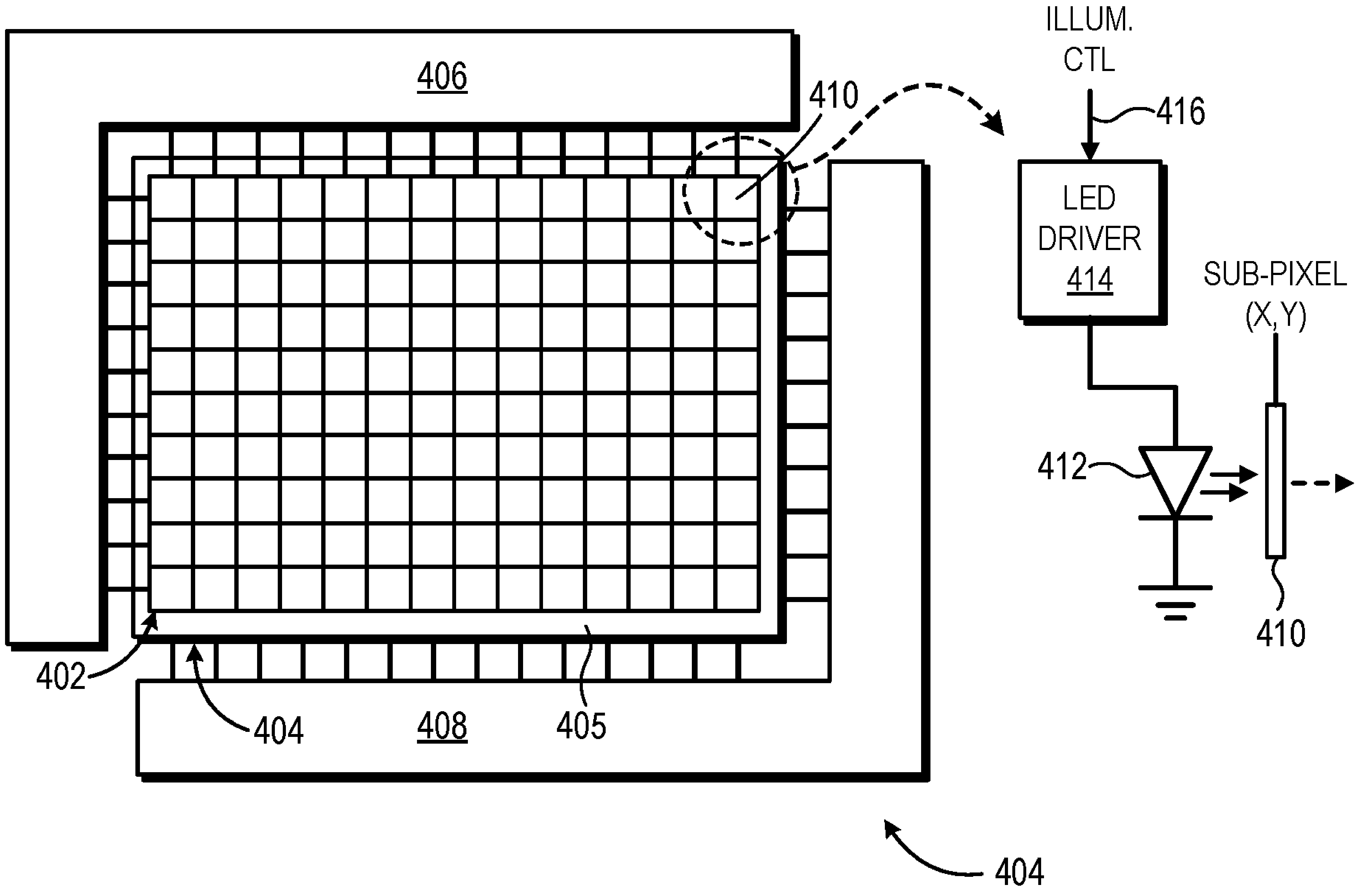

406
410
ILLUM.
CTL
416
LED
DRIVER
414
SUB-PIXEL
(X,Y)
412
410
402
404
408
405
404

FIG. 4

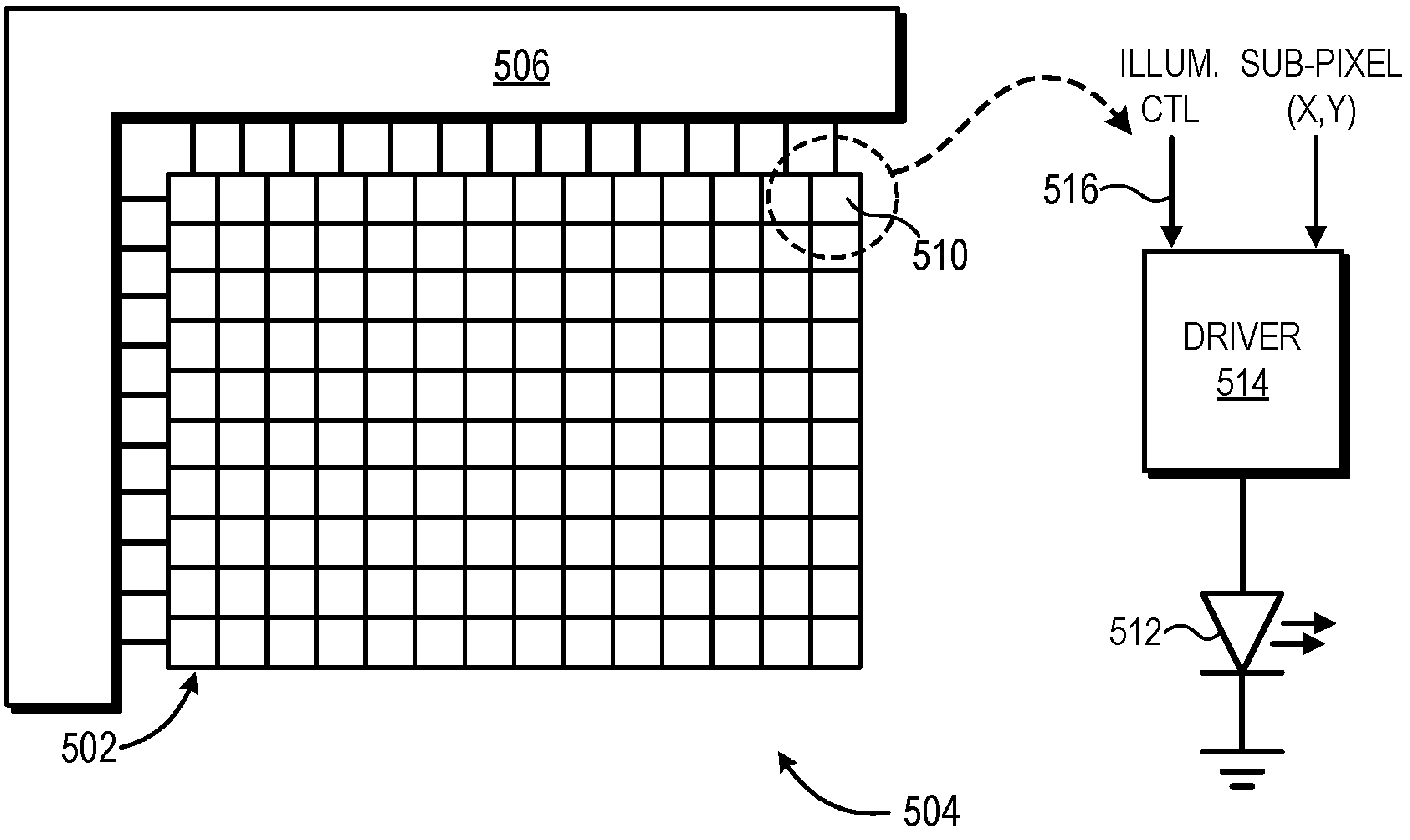

506
ILLUM.
CTL
SUB-PIXEL
(X,Y)
516
510
DRIVER
514
512
502
504

FIG. 5

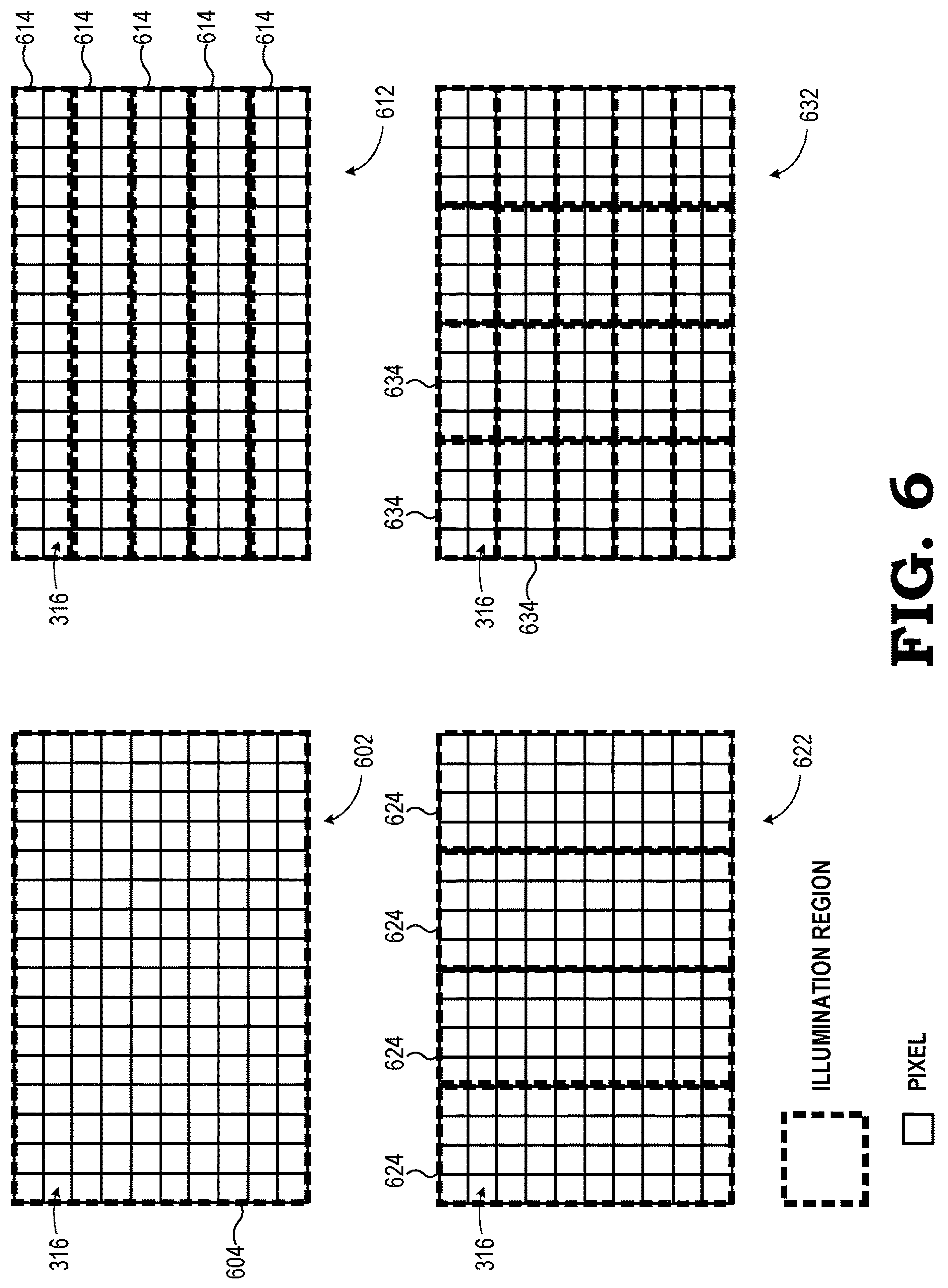

614
614
614
614
614
612
316
634
634
316
634
632
602
316
604
624
624
624
624
622
316
ILLUMINATION REGION
PIXEL

FIG. 6

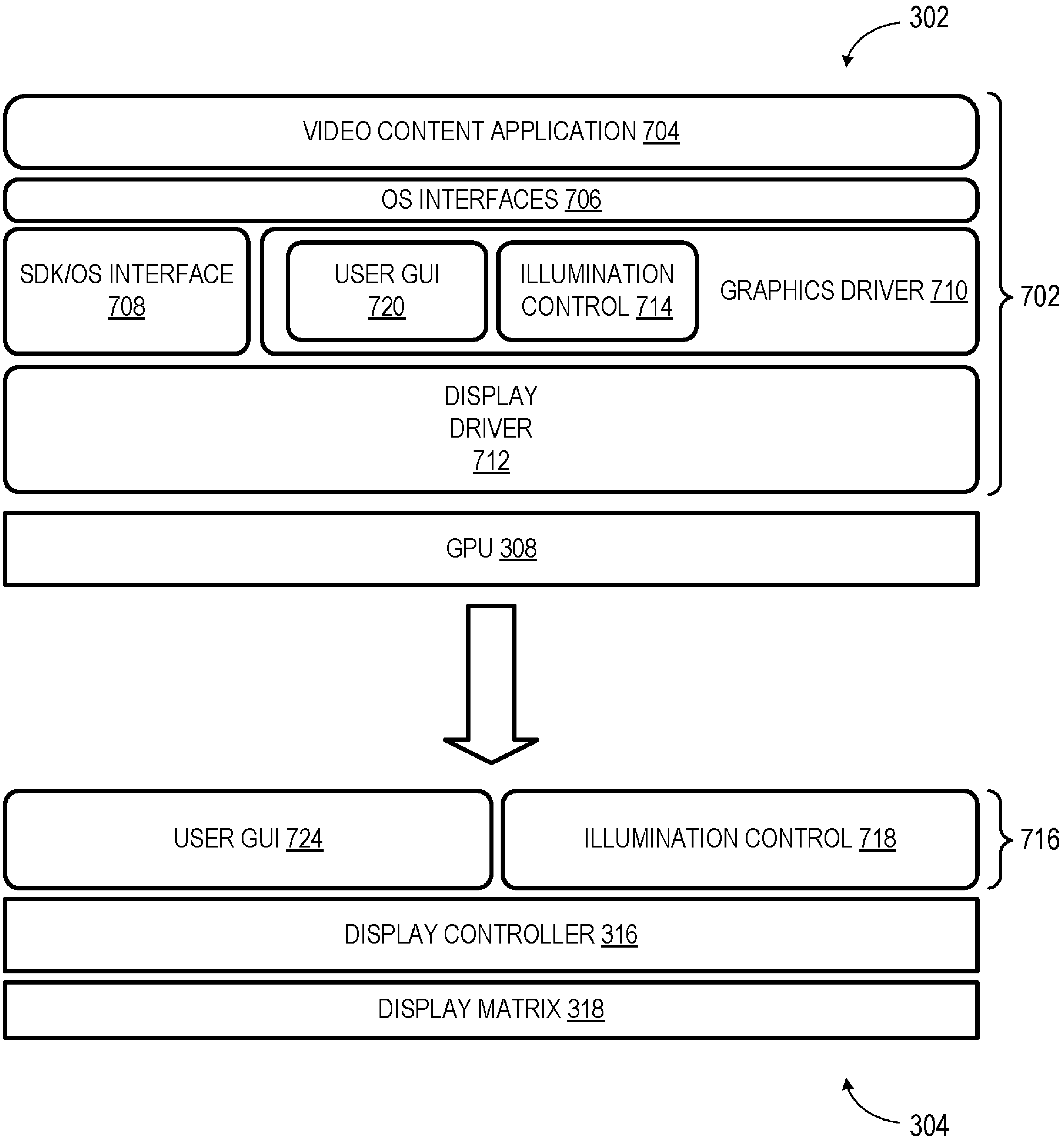

302
VIDEO CONTENT APPLICATION 704
OS INTERFACES 706
SDK/OS INTERFACE 708
USER GUI 720
ILLUMINATION CONTROL 714
GRAPHICS DRIVER 710
702
DISPLAY DRIVER 712
GPU 308
USER GUI 724
ILLUMINATION CONTROL 718
716
DISPLAY CONTROLLER 316
DISPLAY MATRIX 318
304

FIG. 7

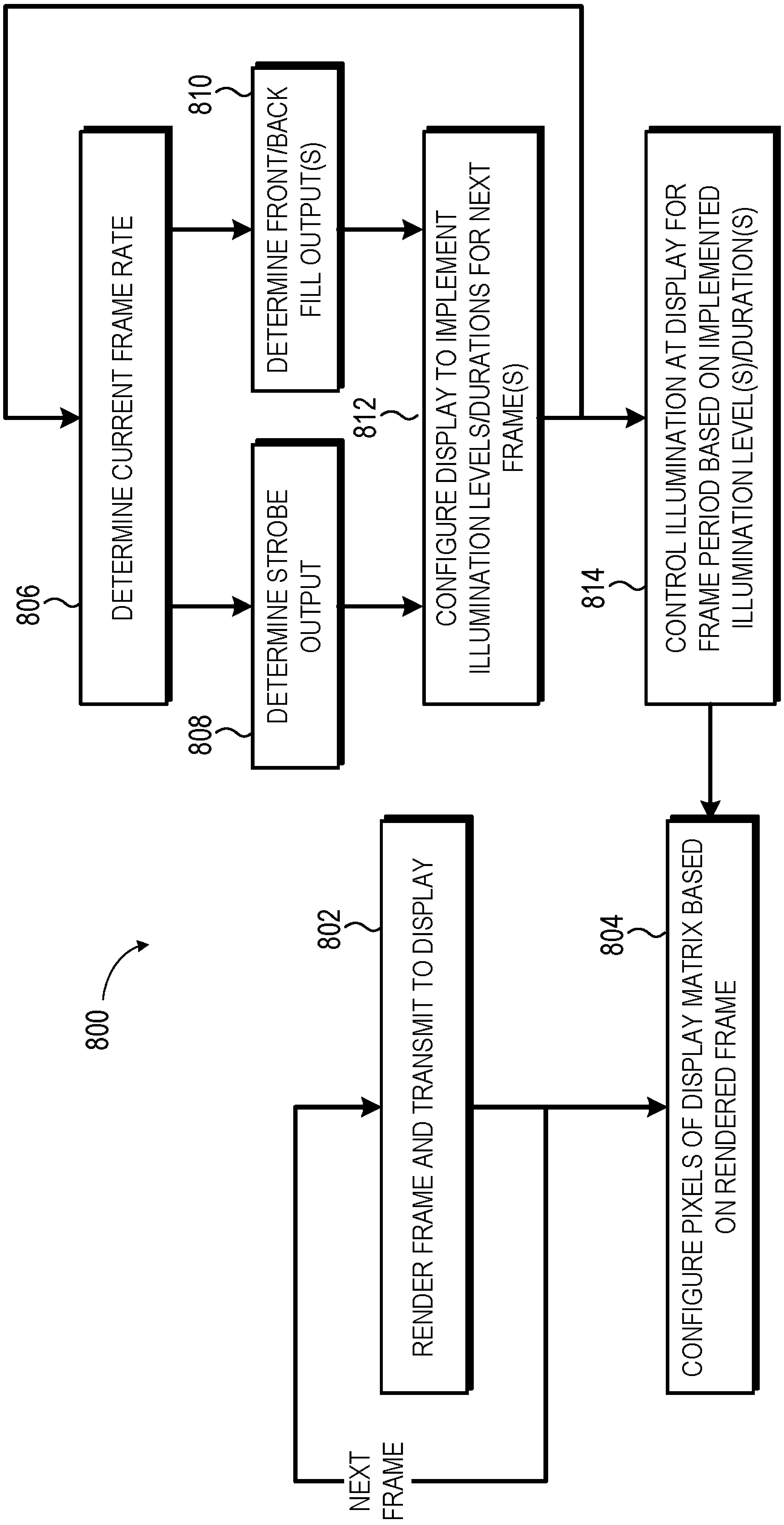

800
802
RENDER FRAME AND TRANSMIT TO DISPLAY
NEXT FRAME
804
CONFIGURE PIXELS OF DISPLAY MATRIX BASED ON RENDERED FRAME
806
DETERMINE CURRENT FRAME RATE
808
DETERMINE STROBE OUTPUT
810
DETERMINE FRONT/BACK FILL OUTPUT(S)
812
CONFIGURE DISPLAY TO IMPLEMENT ILLUMINATION LEVELS/DURATIONS FOR NEXT FRAME(S)
814
CONTROL ILLUMINATION AT DISPLAY FOR FRAME PERIOD BASED ON IMPLEMENTED ILLUMINATION LEVEL(S)/DURATION(S)

FIG. 8

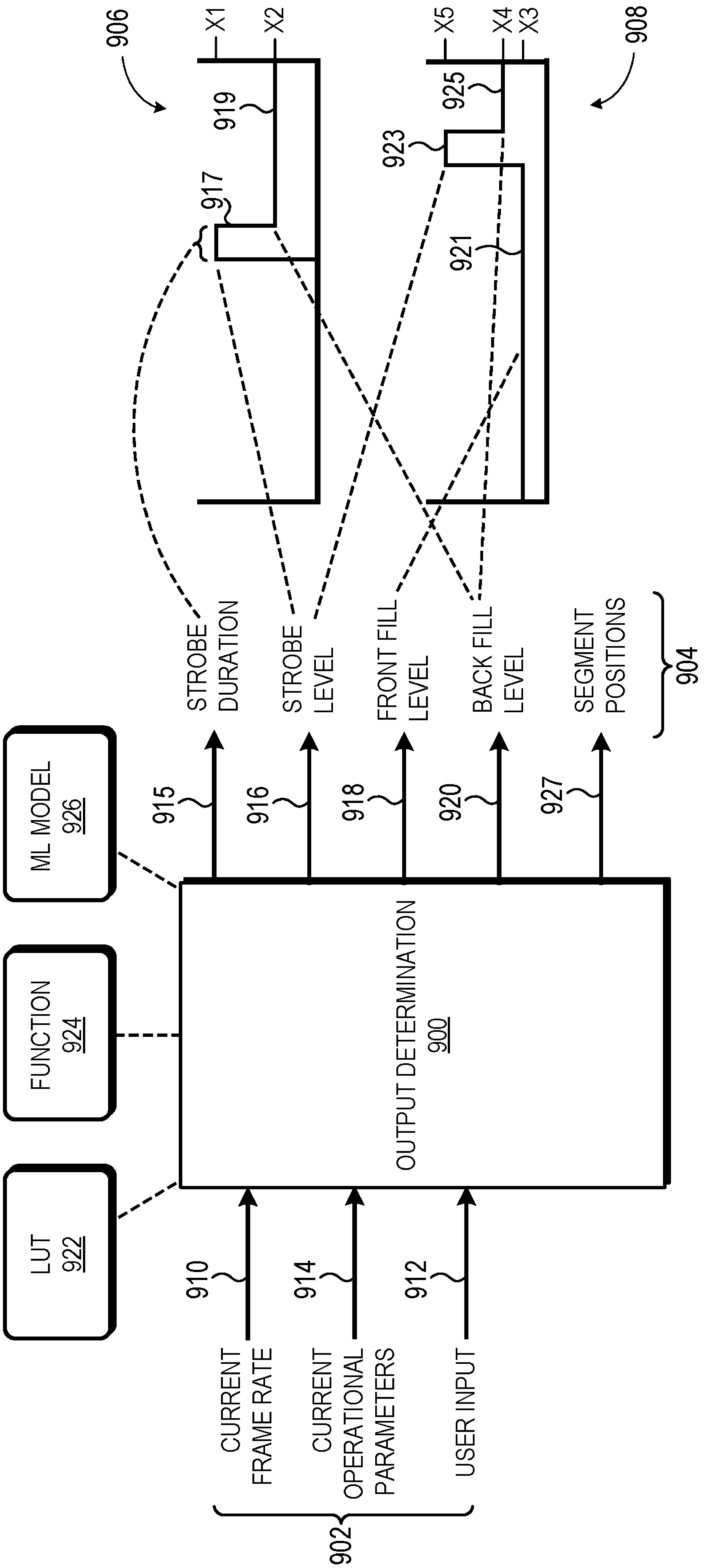

LUT
922
FUNCTION
924
ML MODEL
926
CURRENT
FRAME RATE
CURRENT
OPERATIONAL
PARAMETERS
USER INPUT
902
910
914
912
OUTPUT DETERMINATION
900
915
916
918
920
927
STROBE
DURATION
STROBE
LEVEL
FRONT FILL
LEVEL
BACK FILL
LEVEL
SEGMENT
POSITIONS
904
906
908
X1
X2
X5
X4
X3
917
919
921
923
925

FIG. 9

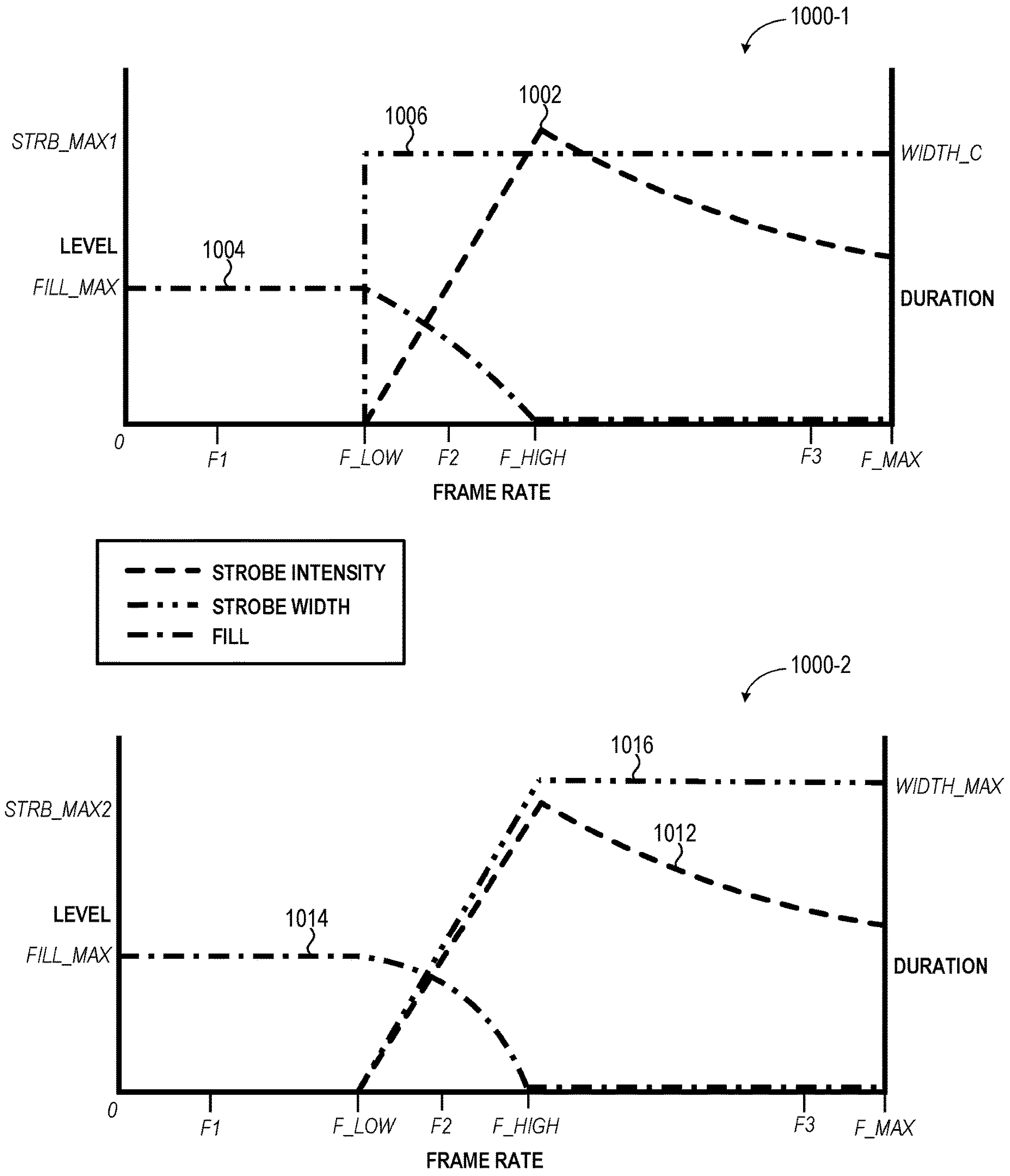

1000-1
1002
1006
STRB_MAX1
WIDTH_C
LEVEL
1004
FILL_MAX
DURATION
0
F1
F_LOW
F2
F_HIGH
F3
F_MAX
FRAME RATE
STROBE INTENSITY
STROBE WIDTH
FILL
1000-2
1016
STRB_MAX2
WIDTH_MAX
1012
LEVEL
1014
FILL_MAX
DURATION
0
F1
F_LOW
F2
F_HIGH
F3
F_MAX
FRAME RATE

FIG. 10

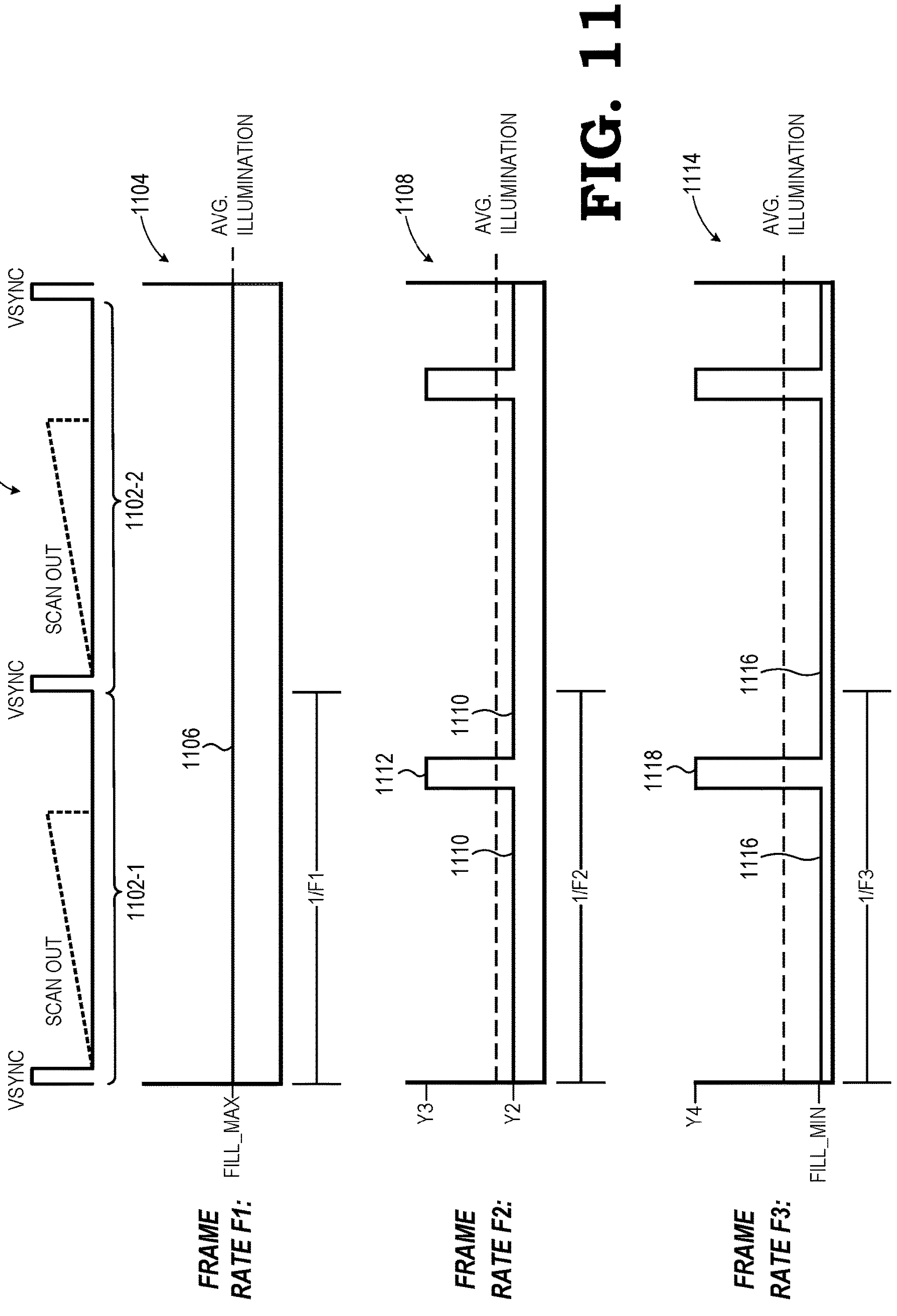


FIG. 11

1100
VSYNC
VSYNC
VSYNC
SCAN OUT
SCAN OUT
1102-1
1102-2
1104
AVG. ILLUMINATION
1106
FILL_MAX
1/F1
FRAME RATE F1:
1108
AVG. ILLUMINATION
1110
1110
1112
Y3
Y2
1/F2
FRAME RATE F2:
1114
AVG. ILLUMINATION
1116
1116
1118
Y4
FILL_MIN
1/F3
FRAME RATE F3:

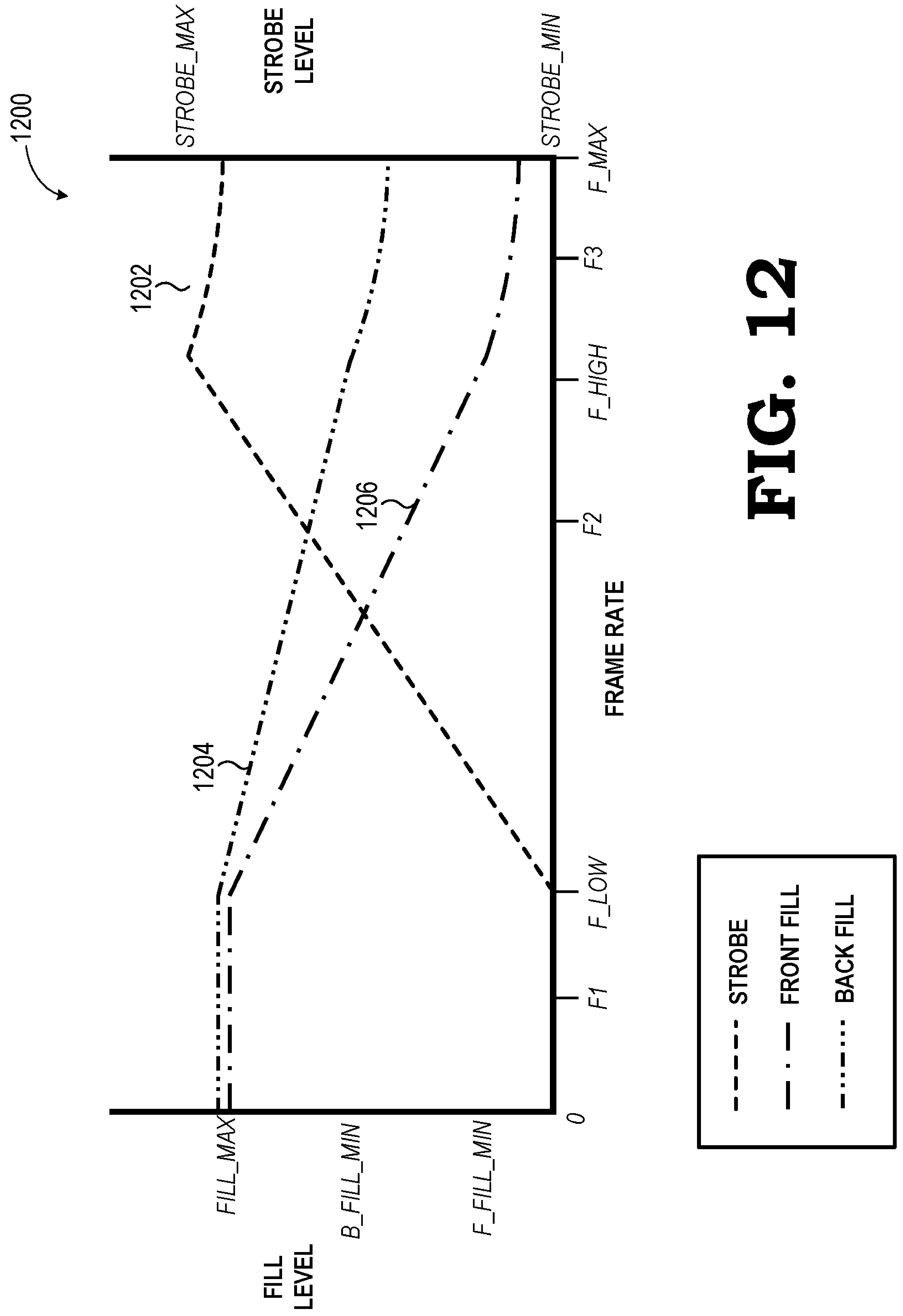

1200
STROBE_MAX
STROBE LEVEL
STROBE_MIN
1202
1204
1206
FILL_MAX
B_FILL_MIN
F_FILL_MIN
FILL LEVEL
0
F1
F_LOW
F2
F_HIGH
F3
F_MAX
FRAME RATE
STROBE
FRONT FILL
BACK FILL

FIG. 12

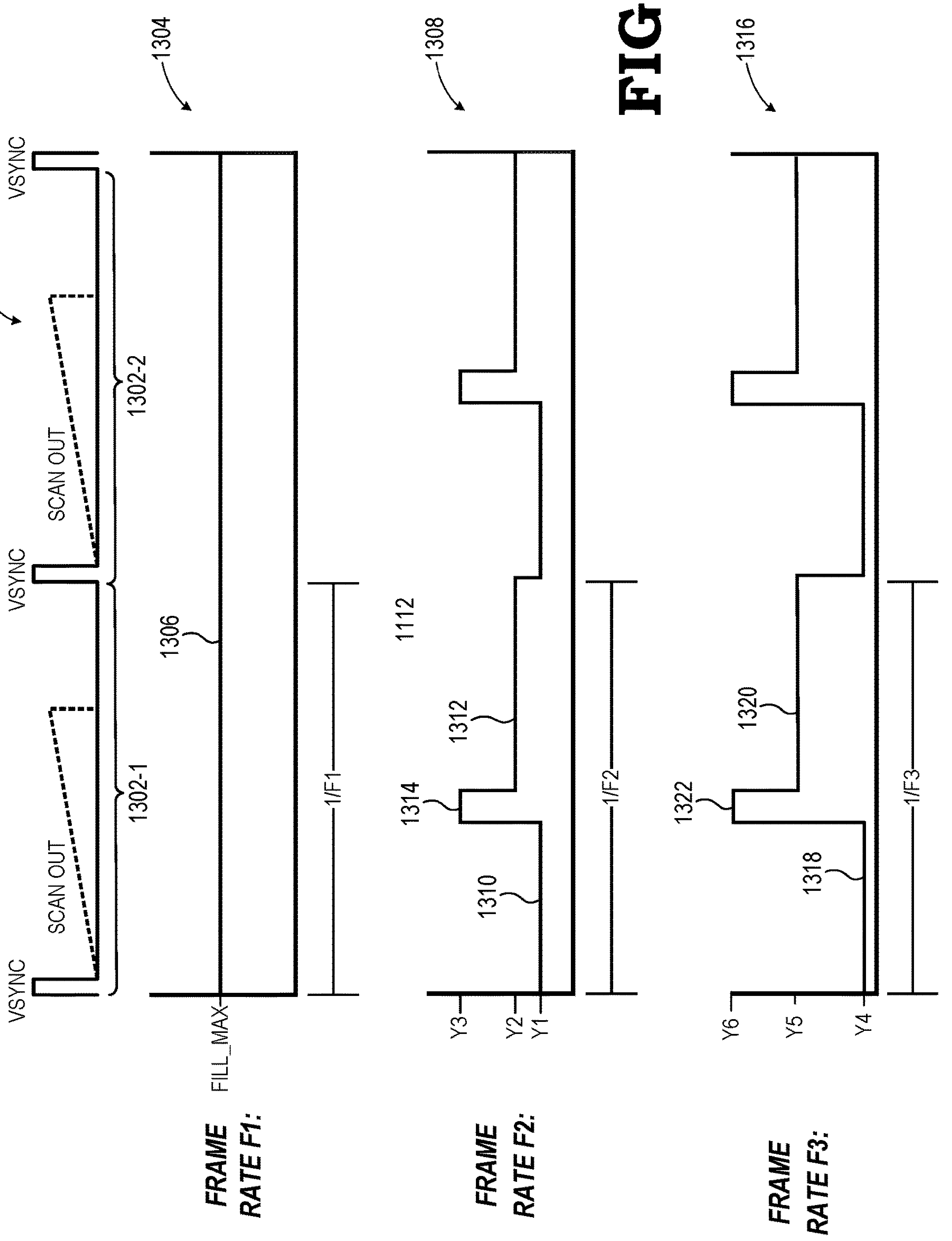

1300
VSYNC
VSYNC
VSYNC
SCAN OUT
SCAN OUT
1302-1
1302-2
1304
1306
FILL_MAX
1/F1
FRAME RATE F1:
1308
1310
1312
1314
1112
Y1
Y2
Y3
1/F2
FRAME RATE F2:
1316
1318
1320
1322
Y4
Y5
Y6
1/F3
FRAME RATE F3:

FIG. 13

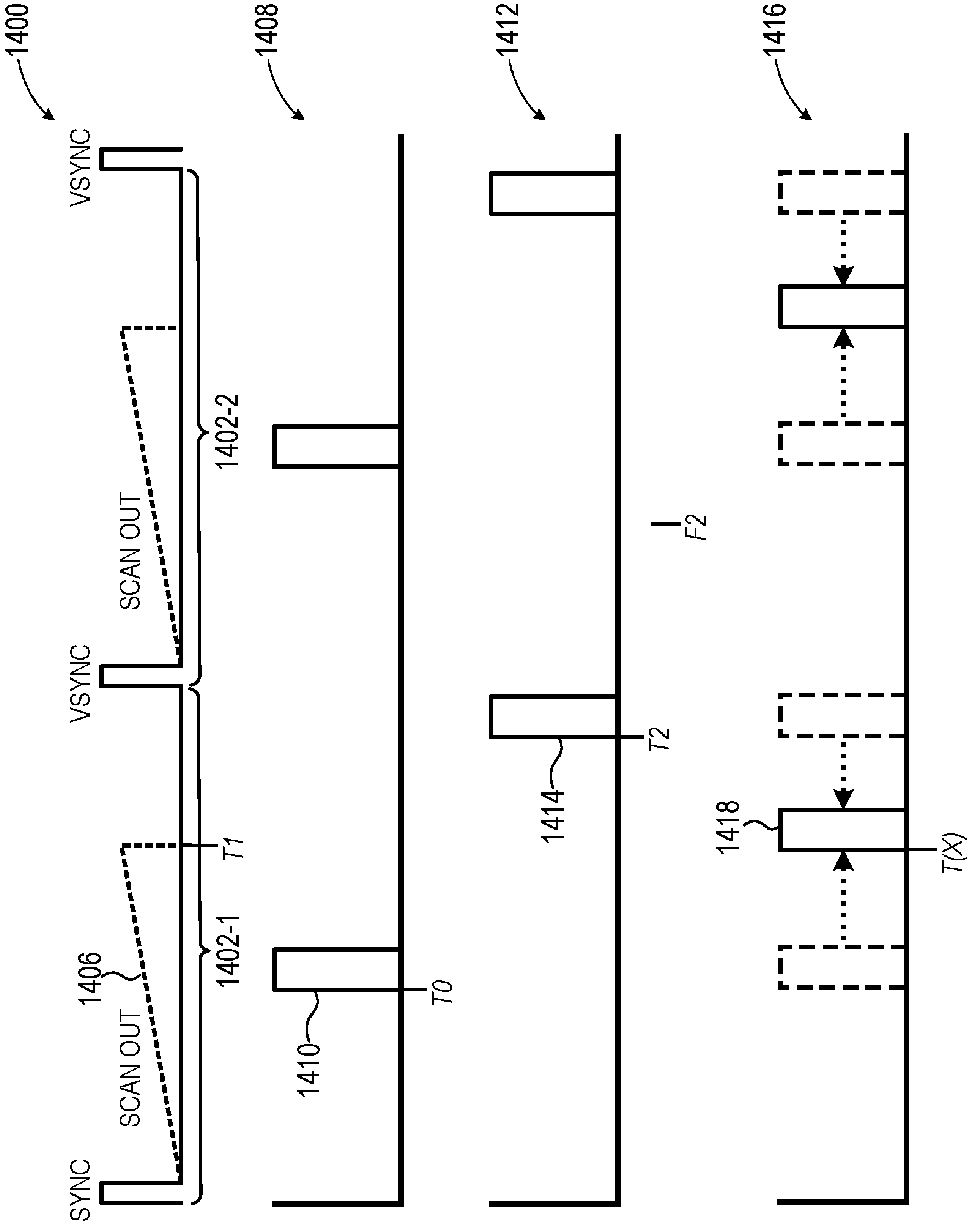

1400
VSYNC
VSYNC
VSYNC
SCAN OUT
SCAN OUT
1406
T1
1402-1
1402-2
1408
1410
T0
1412
1414
T2
F2
1416
1418
T(X)

FIG. 14

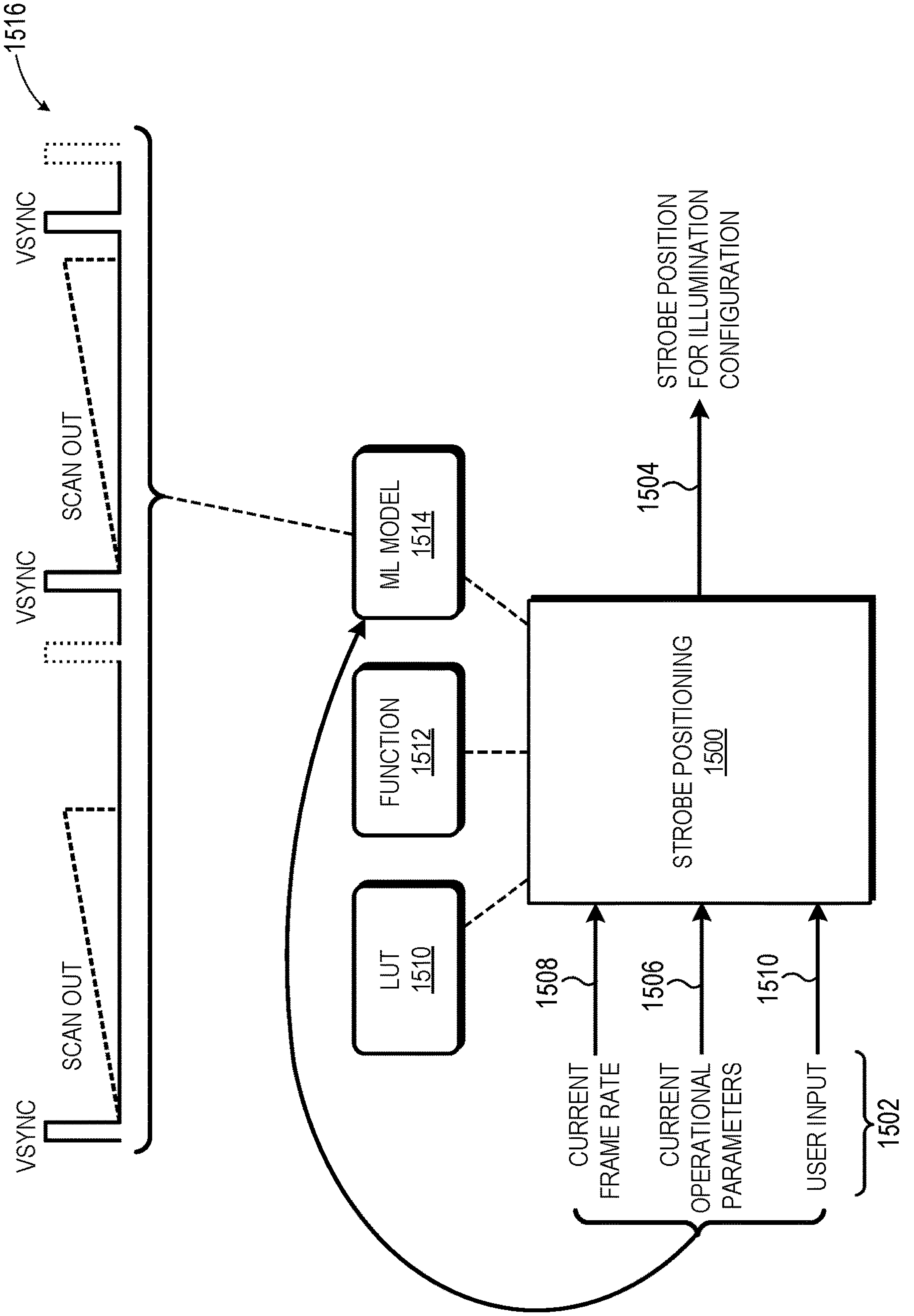
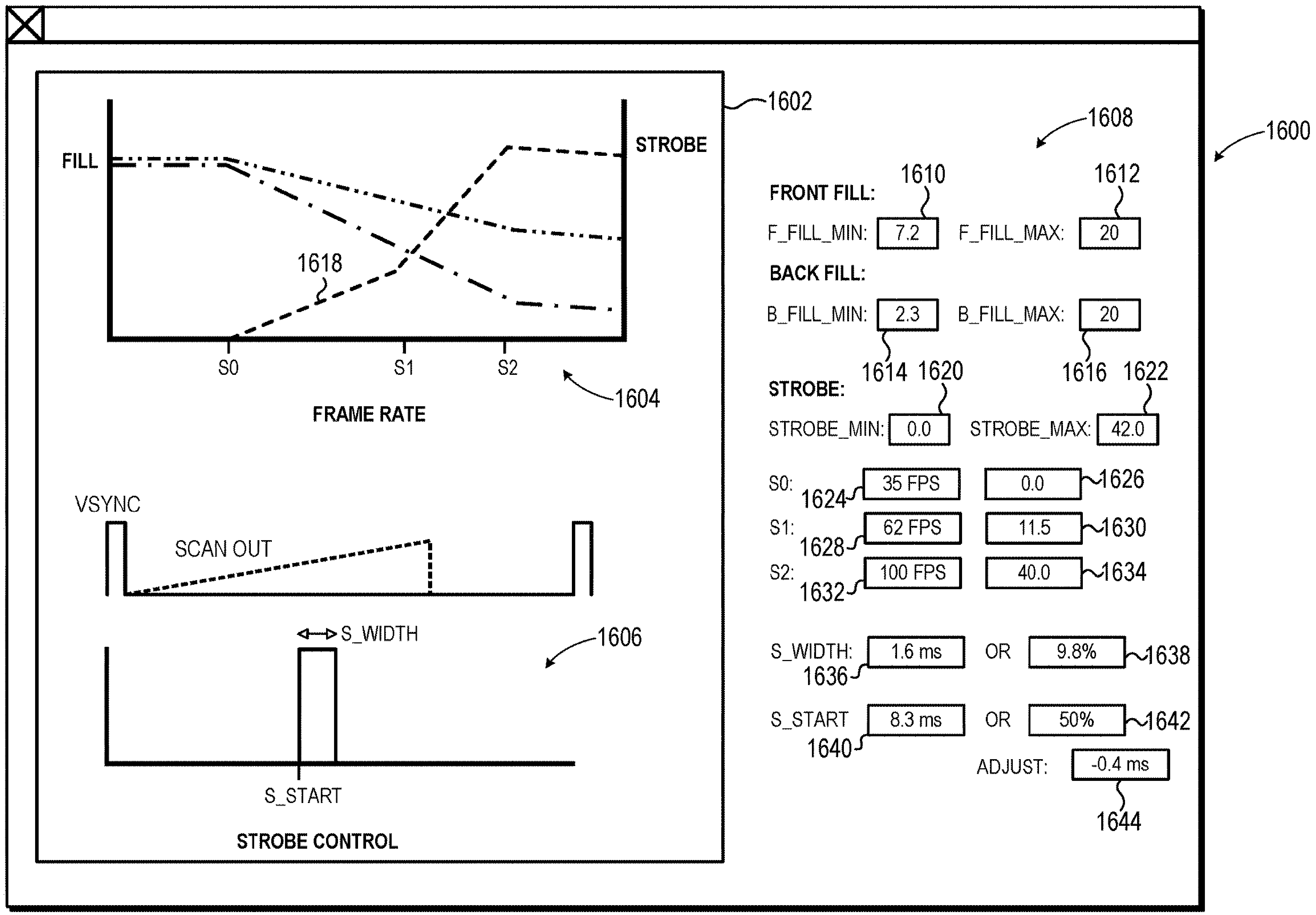

1516
VSYNC
SCAN OUT
VSYNC
SCAN OUT
VSYNC
ML MODEL
1514
FUNCTION
1512
LUT
1510
STROBE POSITIONING
1500
1504
STROBE POSITION
FOR ILLUMINATION
CONFIGURATION
1508
1506
1510
CURRENT
FRAME RATE
CURRENT
OPERATIONAL
PARAMETERS
USER INPUT
1502

FIG. 15



FRONT FILL:

F_FILL_MIN: 7.2 F_FILL_MAX: 20

BACK FILL:

B_FILL_MIN: 2.3 B_FILL_MAX: 20

STROBE:

STROBE_MIN: 0.0 STROBE_MAX: 42.0

S0: 35 FPS 0.0

S1: 62 FPS 11.5

S2: 100 FPS 40.0

S_WIDTH: 1.6 ms OR 9.8%

S_START 8.3 ms OR 50%

ADJUST: -0.4 ms

FIG. 16

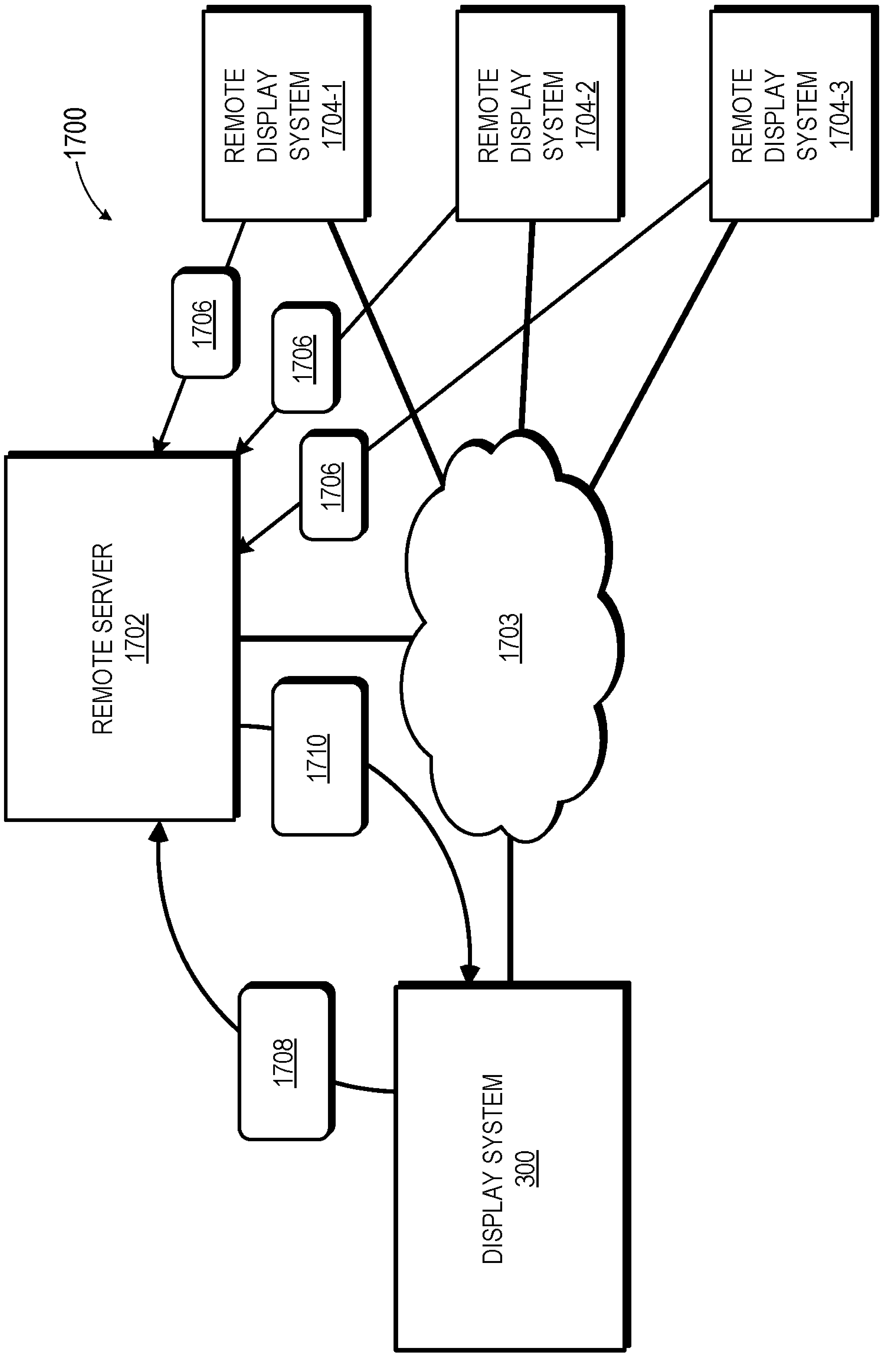

1700
REMOTE DISPLAY SYSTEM 1704-1
REMOTE DISPLAY SYSTEM 1704-2
REMOTE DISPLAY SYSTEM 1704-3
1706
1706
1706
REMOTE SERVER 1702
1703
1710
1708
DISPLAY SYSTEM 300

FIG. 17

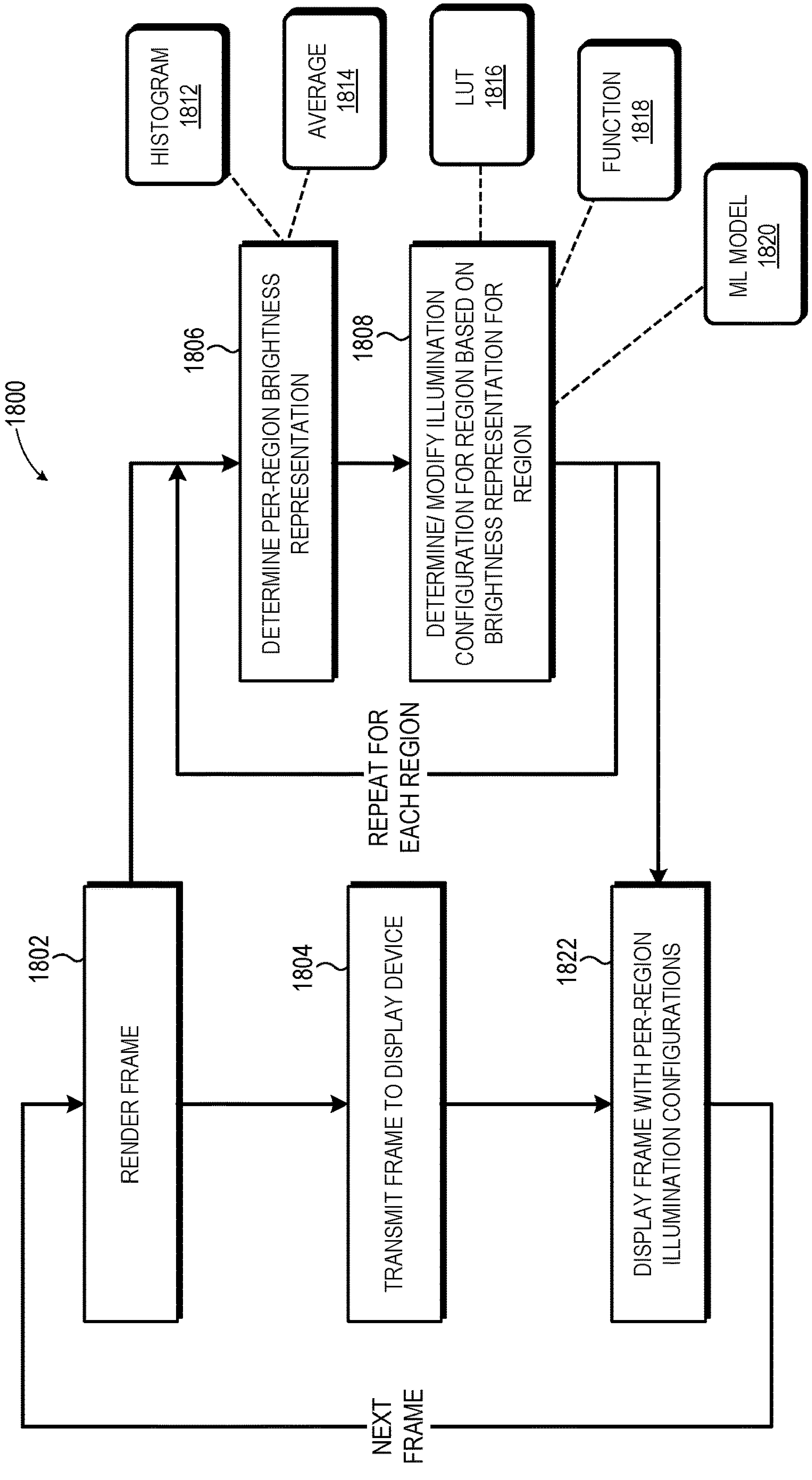

1800
1802
RENDER FRAME
1804
TRANSMIT FRAME TO DISPLAY DEVICE
1822
DISPLAY FRAME WITH PER-REGION ILLUMINATION CONFIGURATIONS
NEXT FRAME
1806
DETERMINE PER-REGION BRIGHTNESS REPRESENTATION
1808
DETERMINE/ MODIFY ILLUMINATION CONFIGURATION FOR REGION BASED ON BRIGHTNESS REPRESENTATION FOR REGION
REPEAT FOR EACH REGION
HISTOGRAM 1812
AVERAGE 1814
LUT 1816
FUNCTION 1818
ML MODEL 1820

FIG. 18

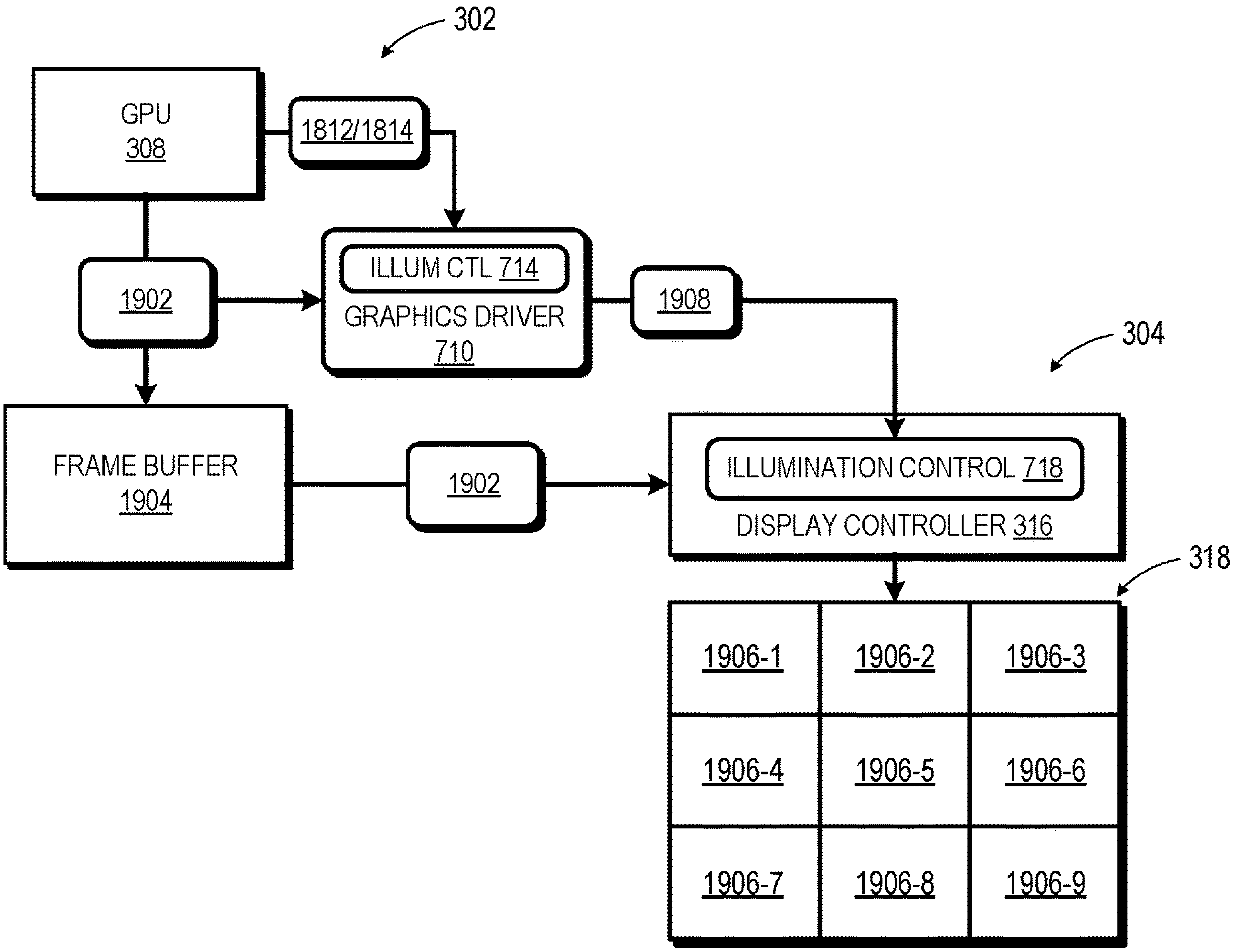

302
GPU 308
1812/1814
1902
ILLUM CTL 714
GRAPHICS DRIVER 710
1908
304
FRAME BUFFER 1904
1902
ILLUMINATION CONTROL 718
DISPLAY CONTROLLER 316
318
1906-1
1906-2
1906-3
1906-4
1906-5
1906-6
1906-7
1906-8
1906-9

FIG. 19

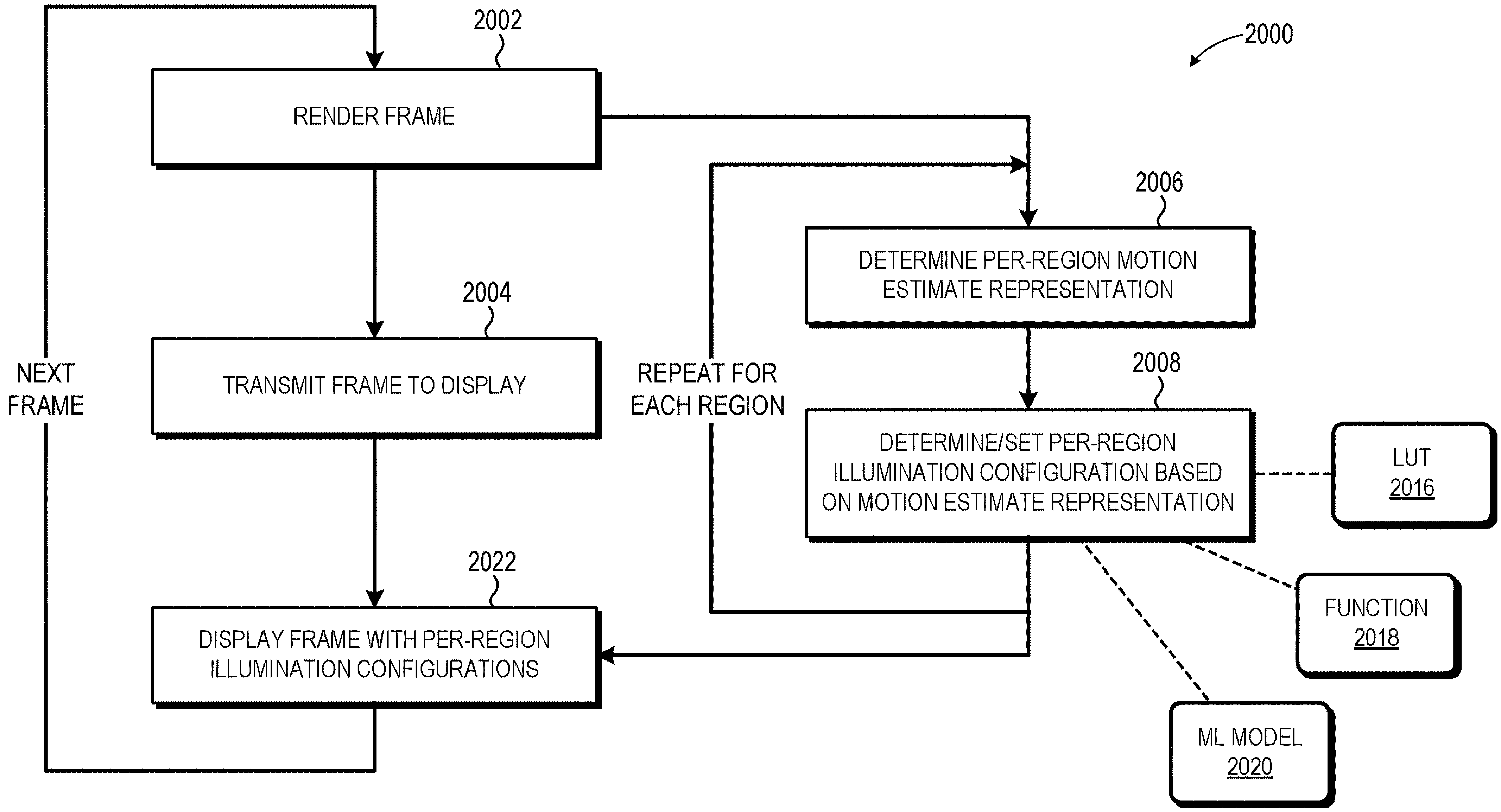

2000
2002
RENDER FRAME
2004
TRANSMIT FRAME TO DISPLAY
2022
DISPLAY FRAME WITH PER-REGION ILLUMINATION CONFIGURATIONS
NEXT FRAME
REPEAT FOR EACH REGION
2006
DETERMINE PER-REGION MOTION ESTIMATE REPRESENTATION
2008
DETERMINE/SET PER-REGION ILLUMINATION CONFIGURATION BASED ON MOTION ESTIMATE REPRESENTATION
LUT 2016
FUNCTION 2018
ML MODEL 2020

FIG. 20

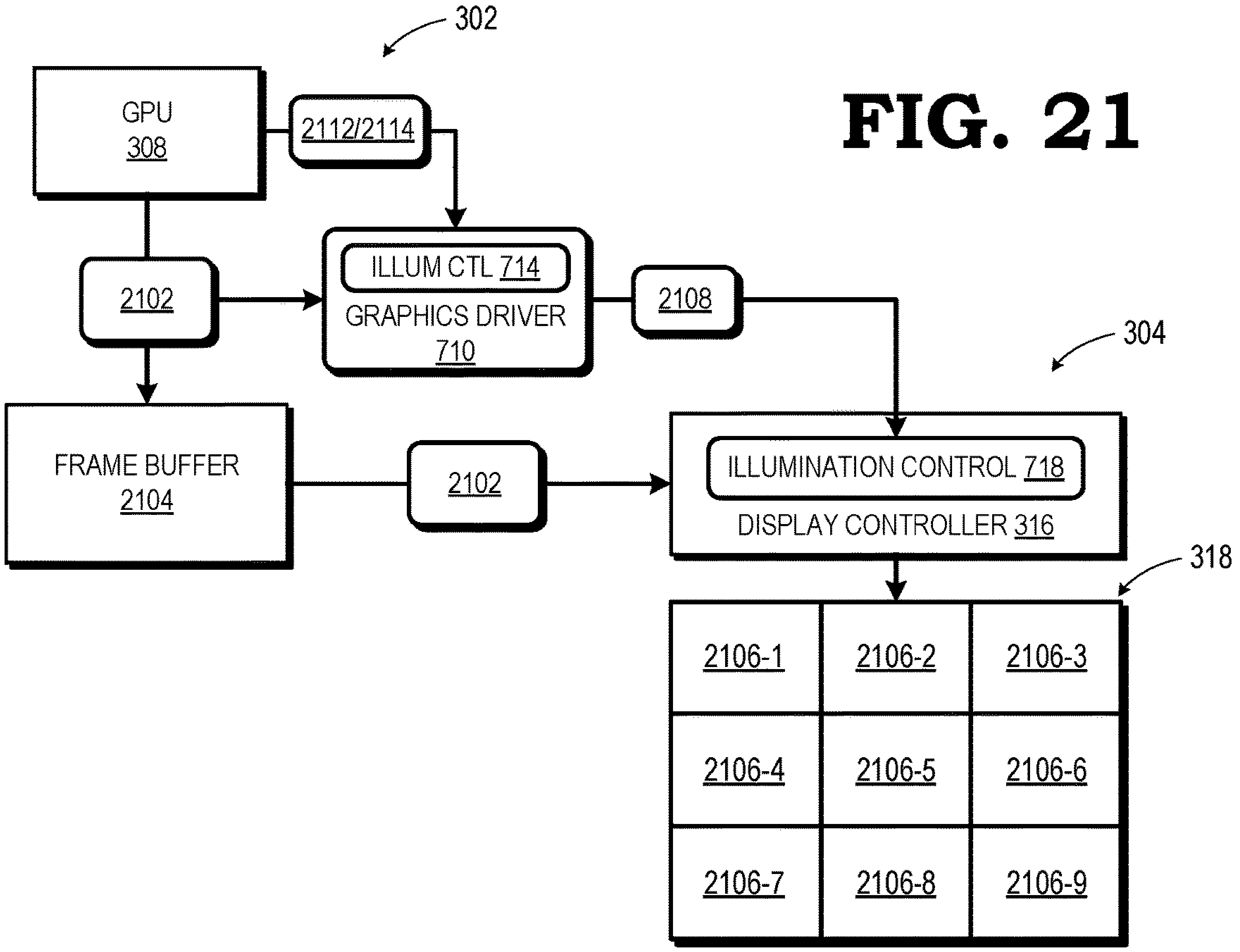

302
GPU 308
2112/2114
ILLUM CTL 714
GRAPHICS DRIVER 710
2102
2108
304
FRAME BUFFER 2104
2102
ILLUMINATION CONTROL 718
DISPLAY CONTROLLER 316
318
2106-1
2106-2
2106-3
2106-4
2106-5
2106-6
2106-7
2106-8
2106-9

FIG. 21

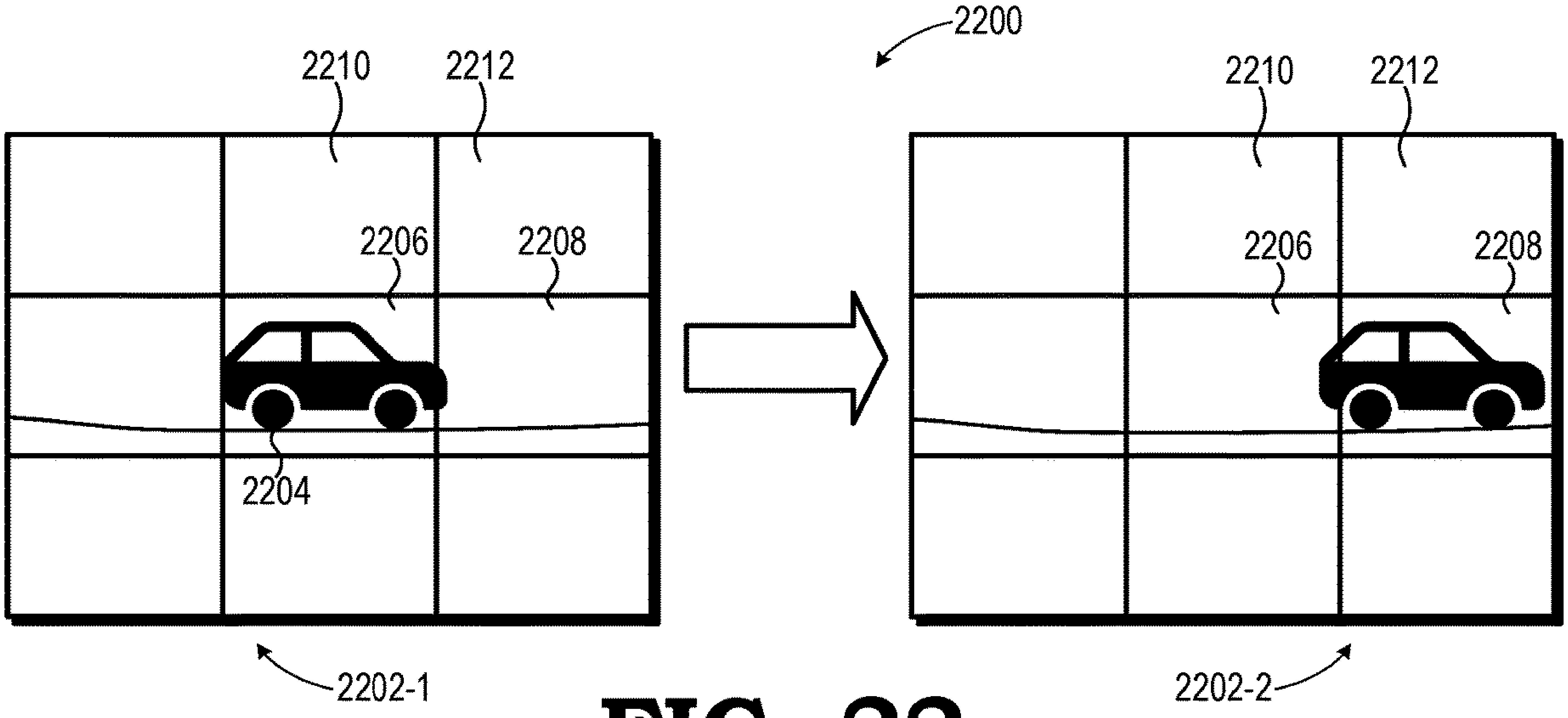

2200
2210
2212
2206
2208
2204
2202-1
2210
2212
2206
2208
2202-2

FIG. 22

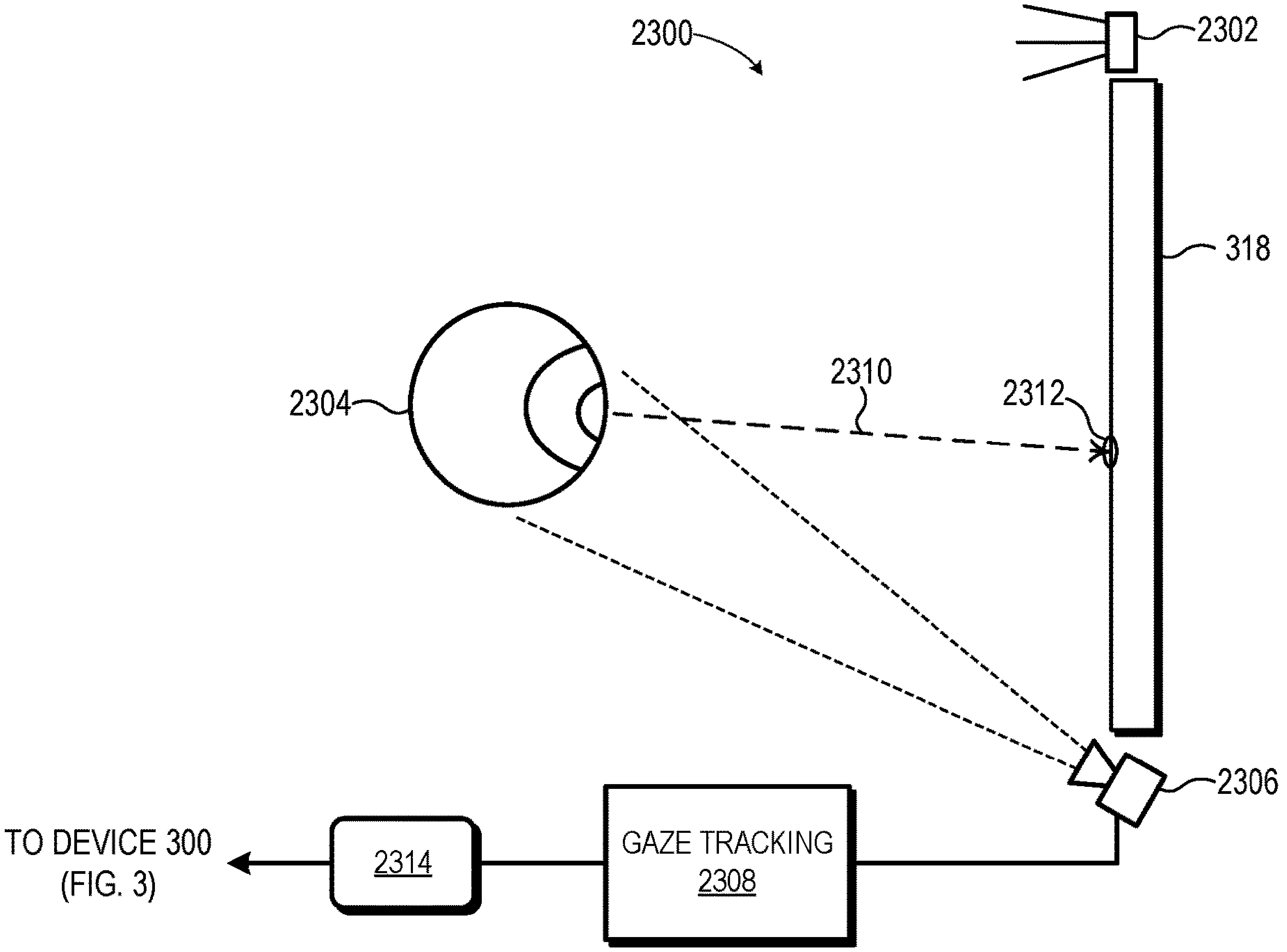

2300
2302
318
2304
2310
2312
2306
TO DEVICE 300
(FIG. 3)
2314
GAZE TRACKING
2308

FIG. 23

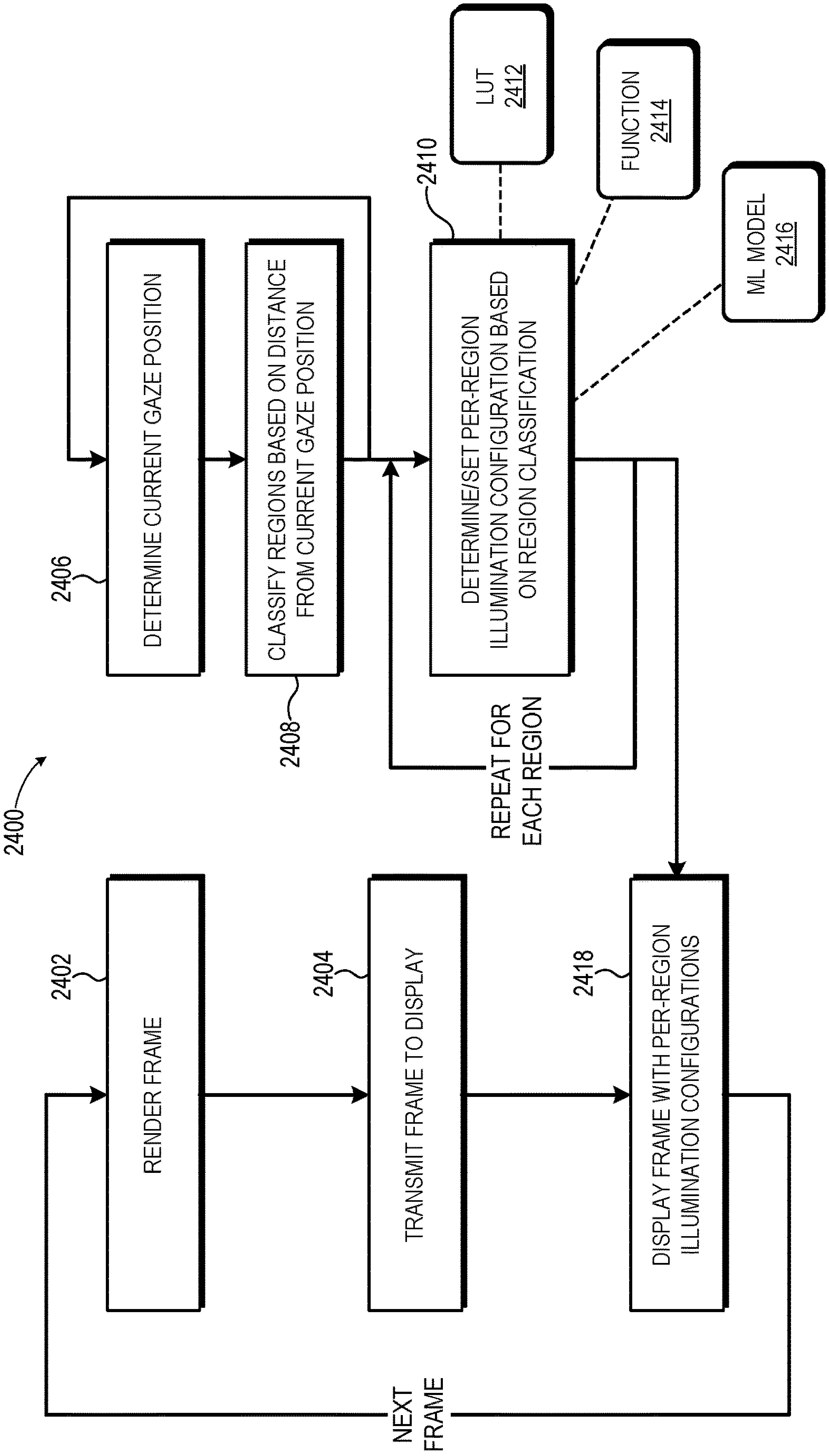

2400
2402
RENDER FRAME
2404
TRANSMIT FRAME TO DISPLAY
2418
DISPLAY FRAME WITH PER-REGION ILLUMINATION CONFIGURATIONS
NEXT FRAME
2406
DETERMINE CURRENT GAZE POSITION
2408
CLASSIFY REGIONS BASED ON DISTANCE FROM CURRENT GAZE POSITION
2410
DETERMINE/SET PER-REGION ILLUMINATION CONFIGURATION BASED ON REGION CLASSIFICATION
REPEAT FOR EACH REGION
LUT 2412
FUNCTION 2414
ML MODEL 2416

FIG. 24

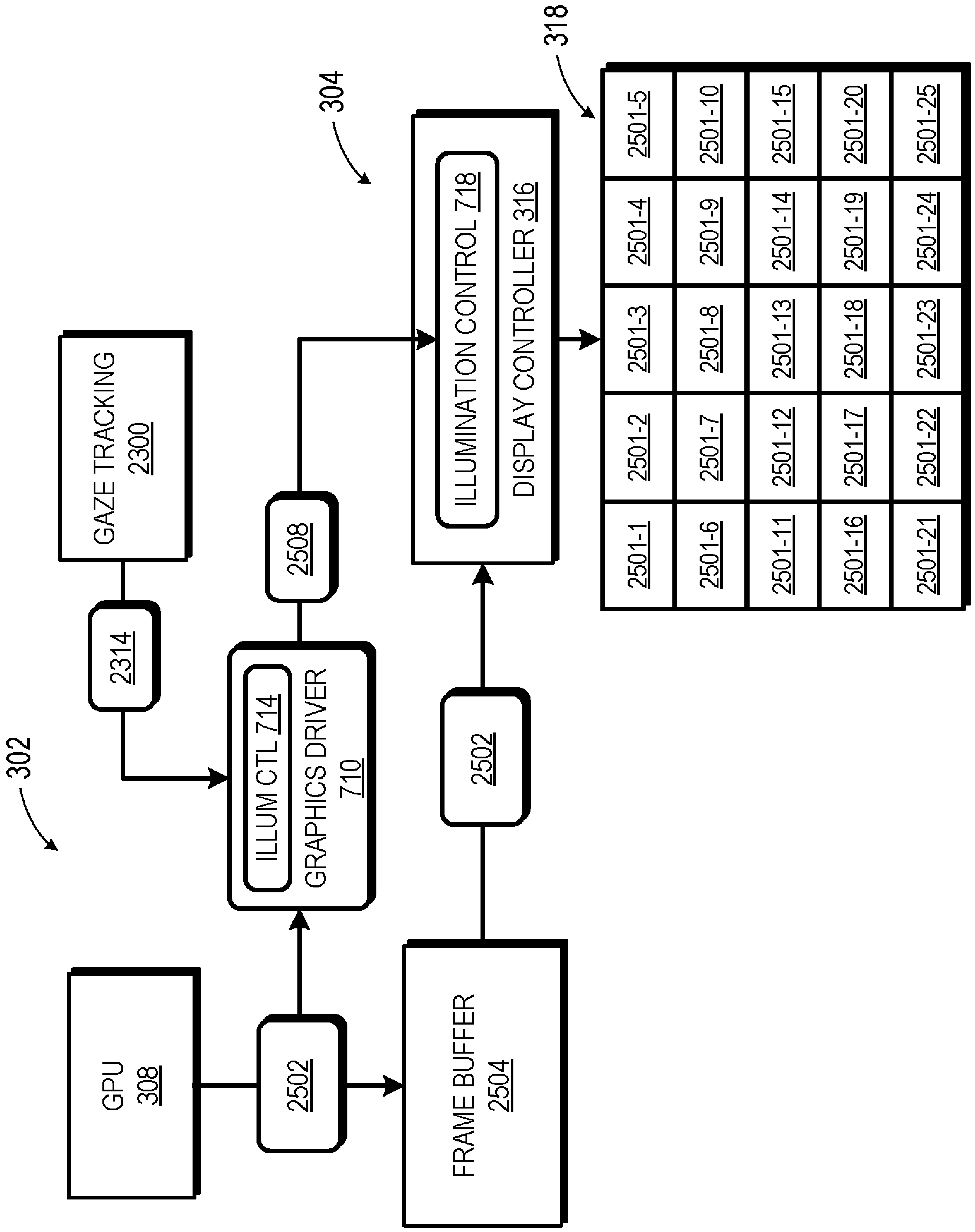

302
GPU
308
2502
FRAME BUFFER
2504
ILLUM CTL 714
GRAPHICS DRIVER
710
2314
GAZE TRACKING
2300
2502
2508
304
ILLUMINATION CONTROL 718
DISPLAY CONTROLLER 316
318
2501-1
2501-2
2501-3
2501-4
2501-5
2501-6
2501-7
2501-8
2501-9
2501-10
2501-11
2501-12
2501-13
2501-14
2501-15
2501-16
2501-17
2501-18
2501-19
2501-20
2501-21
2501-22
2501-23
2501-24
2501-25

FIG. 25

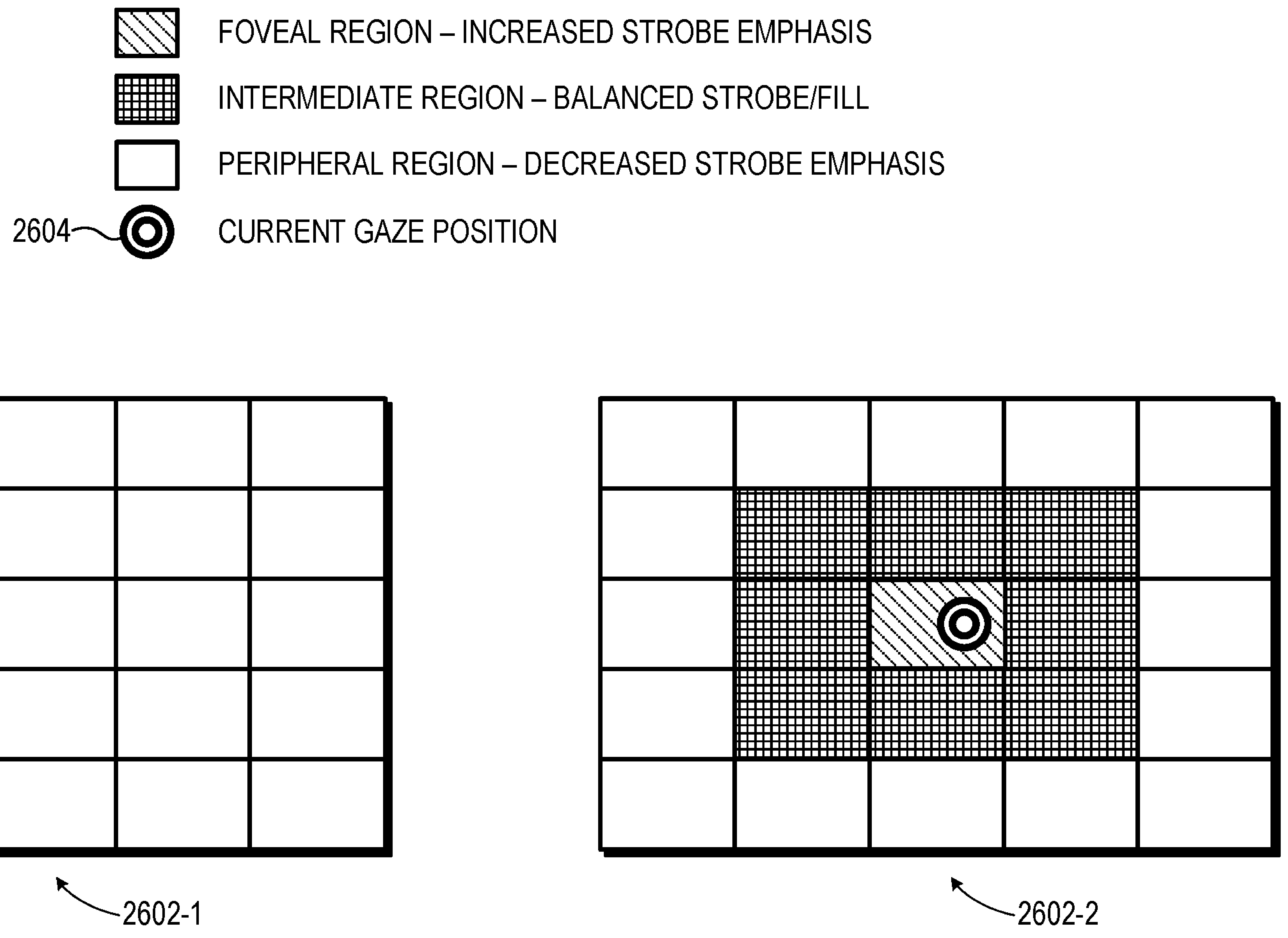

FOVEAL REGION – INCREASED STROBE EMPHASIS
INTERMEDIATE REGION – BALANCED STROBE/FILL
PERIPHERAL REGION – DECREASED STROBE EMPHASIS
2604
CURRENT GAZE POSITION
2602-1
2602-2

FIG. 26

STROBE CONFIGURATION FOR ILLUMINATION OF FRAME AT DISPLAY DEVICE

CROSS-REFERENCE TO RELATED APPLICATIONS

The present application claims priority to the following provisional patent applications, the entireties of which are incorporated by reference herein: U.S. Provisional Patent Application Ser. No. 62/788,536, filed on Jan. 4, 2019 and entitled "Variable Strobe Light Amount Based on Frame Rate or Foveal Area"; and U.S. Provisional Patent Application Ser. No. 62/853,032, filed on May 26, 2019 and entitled "Illumination Control at Display Device".

The present application is related to the following co-pending patent applications, the entirety of which are incorporated by reference herein:

U.S. patent application Ser. No. 16/670,618, entitled "FRAME-RATE BASED ILLUMINATION CONTROL AT DISPLAY DEVICE" and filed on even date herewith;

U.S. patent application Ser. No. 16/670,673, entitled "REGION-BY-REGION ILLUMINATION CONTROL AT DISPLAY DEVICE BASED ON PER-REGION BRIGHTNESS" and filed on even date herewith;

U.S. patent application Ser. No. 16/670,651, entitled "REGION-BY-REGION ILLUMINATION CONTROL AT DISPLAY DEVICE BASED ON PER-REGION MOTION ESTIMATION" and filed on even date herewith; and

U.S. patent application Ser. No. 16/670,664, entitled "FOVEATED ILLUMINATION CONTROL AT DISPLAY DEVICE" and filed on even date herewith.

BACKGROUND

Liquid crystal displays (LCDs), light emitting diode (LED) displays, organic LED (OLED) displays, and other emissive, transmissive, and reflective displays conventionally implement one of two illumination configurations: a constant illumination configuration in which the backlight or emissive pixel elements are constantly active at a fixed level for the duration of each frame period; and a strobe configuration in which the backlight or emissive pixel elements are strobed (or "flashed") for only a brief portion of each frame period and otherwise deactivated in the periods proceeding and following the strobe. Displays implementing a constant illumination configuration typically exhibit little if any flicker as the illumination level is constant across each frame period and between each frame period. However, any movement of objects in the displayed content between frames is susceptible to motion blur due to the persistence of vision phenomenon exhibited by the human visual system. Conversely, displays implementing a strobe configuration typically exhibit substantially reduced motion blur due to the brief illumination period during each frame period, but the strobing of the backlight or emissive pixel elements introduces flicker that has the potential to detract from a user's experience. Moreover, the current flows required to provide a sufficiently bright strobe so as to maintain a sufficient average brightness over a series of frame periods typically results in shortened lifespans for the backlight drivers providing such current flows or the emissive pixel elements providing the flashed light.

BRIEF DESCRIPTION OF THE DRAWINGS

The present disclosure is better understood, and its numerous features and advantages made apparent to those skilled

in the art by referencing the accompanying drawings. The use of the same reference symbols in different drawings indicates similar or identical items.

FIG. **1** is a diagram illustrating illumination control during display of frames at a display device in accordance with some embodiments.

FIG. **2** is a diagram illustrating various illumination control techniques and their combinations in accordance with some embodiments.

FIG. **3** is a block diagram illustrating a display system employing one or more illumination control techniques in accordance with some embodiments.

FIG. **4** is a block diagram illustrating an example transmissive-type display device in accordance with some embodiments.

FIG. **5** is a block diagram illustrating an example emissive-type display device in accordance with some embodiments.

FIG. **6** is a block diagram illustrating various example display device configurations for regional illumination control in accordance with some embodiments.

FIG. **7** is a block diagram illustrating a software/hardware stack implemented by the display system of FIG. **3** in accordance with some embodiments.

FIG. **8** is a flow diagram illustrating a method for frame rate-based illumination control of a display device in accordance with some embodiments.

FIG. **9** is a diagram illustrating a technique for determining strobe and fill illumination outputs based on frame rate in accordance with some embodiments.

FIG. **10** is a diagram illustrating example relationships between strobe and after-strobe fill illumination outputs based on frame rate in accordance with some embodiments.

FIG. **11** is a diagram illustrating example illumination configurations for a display device at different frame rates based on the relationship of FIG. **10** in accordance with some embodiments.

FIG. **12** is a diagram illustrating an example relationship between strobe, before-strobe fill, and after-strobe illumination outputs based on frame rate in accordance with some embodiments.

FIG. **13** is a diagram illustrating example illumination configurations for a display device at different frame rates based on the relationship of FIG. **12** in accordance with some embodiments.

FIG. **14** is a diagram illustrating example illumination strobe timings in accordance with some embodiments.

FIG. **15** is a diagram illustrating a technique for illumination strobe timing in accordance with some embodiments.

FIG. **16** is a diagram illustrating a graphical user interface to facilitate receipt of user input on various illumination control parameters in accordance with some embodiments.

FIG. **17** is a diagram illustrating a technique for crowd-sourced illumination control in accordance with some embodiments.

FIG. **18** is a flow diagram illustrating a method for per-region illumination control based on regional brightness in accordance with some embodiments.

FIG. **19** is a diagram illustrating an example implementation for the method of FIG. **18** in accordance with some embodiments.

FIG. **20** is a flow diagram illustrating a method for per-region illumination control based on regional motion estimations in accordance with some embodiments.

FIG. **21** is a diagram illustrating an example implementation for the method of FIG. **20** in accordance with some embodiments.

FIG. **22** is a diagram illustrating an example application of the method of FIG. **20** to two successive frames in accordance with some embodiments.

FIG. **23** is a diagram illustrating a gaze tracking subsystem for the display system of FIG. **3** in accordance with some embodiments.

FIG. **24** is a flow diagram illustrating a method for foveated illumination control in accordance with some embodiments.

FIG. **25** is a diagram illustrating an example implementation for the method of FIG. **24** in accordance with some embodiments.

FIG. **26** is a diagram illustrating an example application of the method of FIG. **24** to two successive frames in accordance with some embodiments.

DETAILED DESCRIPTION

In the following description, numerous specific details are set forth to provide a thorough understanding of the systems and techniques presented herein. However, one having ordinary skill in the art should recognize that the various embodiments can be practiced without these specific details. In some instances, well-known structures, components, signals, computer program instructions, and techniques have not been shown in detail to avoid obscuring the approaches described herein. Moreover, it will be appreciated that for simplicity and clarity of illustration, elements shown in the figures have not necessarily been drawn to scale. For example, the dimensions of some of the elements could be exaggerated relative to other elements.

Display devices present video, graphics, and other imagery to a user through the display of sequences of display frames (hereinafter, simply "frames"), with the display of each frame of a sequence being associated with a corresponding frame period, which is the inverse of the frame rate of the corresponding sequence. Each frame is rendered or otherwise generated and the pixel data representing the frame is buffered in a frame buffer or other storage component. As illustrated by timing chart **100** of FIG. **1**, at the start of a frame period **102-1** (signaled by, for example, assertion of a vertical sync (VSYNC) **104-1** or a vertical blanking interval (VBI)), the pixel data for the frame to be displayed during the frame period is scanned out of the frame buffer on a row-by-row basis and transmitted to the display device (as represented by scan out line **106**), whereupon the display device configures a corresponding row of a pixel matrix composed of, for example, a matrix of liquid crystals (LCs), light emitting diodes (LEDs) or organic LEDs (OLEDs), based on the pixel data of the row of the frame currently being scanned in. The display device causes the "display" of the frame through the emission of display light that is modulated at each pixel in accordance with the pixel data associated with that pixel's location. For liquid crystal displays (LCDs) and other transmissive-type display devices, the emission of display light is achieved through the use of a white backlight and through configuration of each LC at a pixel location based on the pixel data for that pixel location so as to modulate the frequency and intensity of the backlight passing through the LC so that the resulting transmitted light has a corresponding color and intensity. Reflective-type displays operate in a similar manner, but using reflected light rather than backlighting. For LED displays, OLED displays, and other emissive-type display devices, the emission of display light is achieved through activation of the LED or OLED subpixels of different colors (e.g., red, green, and blue) at different intensities so that the combined light emitted by the subpixels combines to provide a particular color and intensity corresponding to the pixel data associated with that pixel.

Whether through emissive, transmissive, or reflection of light, the portion of the frame period during which display light is being generated by the display device so as to display a corresponding frame to a user is referred to herein as the "illumination" of the frame. Some conventional display systems employ a constant illumination approach in which the illumination intensity is maintained at a constant level for the entire duration of the frame period. To illustrate, timing chart **110** of FIG. **1** illustrates a conventional constant illumination technique in which a display device controls the illumination source(s) (e.g., the backlight for an LCD display or the pixels themselves for an LED or LED display) so that the light output **112** is maintained at a constant level L across the entire frame period for each frame period **102-1**, **102-2**, and so on. This approach typically eliminates display flicker as the illumination level is constant within the frame period and between frame periods, but can instill motion blur for display content in motion between successive frames due to the persistence of vision phenomenon.

Accordingly, to mitigate motion blur, some conventional display systems employ an opposite approach in which illumination occurs for only a brief portion of the frame period, with this brief illumination referred to as an illumination "strobe" (or "flash"). To illustrate, timing chart **120** illustrates a conventional strobed illumination technique in which a display device controls the illumination source(s) so that the light output **122** of the illumination sources is non-zero for only a relatively-small portion of each frame period **102** (that is, no greater than 25%, 20%, 15%, or even 10% of the frame period), and thus effectively forming an illumination strobe **124** that is activated briefly during the frame period **102** (e.g., 0.5 to 2 milliseconds). While this results in the frame being "displayed" as emitted display light for only a relatively short period of time and thus substantially avoiding image persistence and therefore mitigating motion blur, the illumination strobe **124** occurring during each frame period **102** introduces a low-frequency flashing that can be perceived by some users as display flicker. Moreover, to provide an adequate average brightness level, the intensity level of the illumination strobe **124** generally must be set substantially higher than the intensity level needed for the constant illumination approach, and thus results in substantial current outflow by the drivers of the illumination source(s) during the illumination strobe **124**. This increased current outflow typically results in a decreased lifespan for the illumination source or requires implementation of heavier-duty driver circuitry, which often is cost prohibitive. Moreover, the timing of the strobe **124** itself can impact the display of the frame, with a strobe occurring earlier in the frame period providing reduced latency but increased potential for ghosting, while a later-occurring strobe can reduce or eliminate ghosting but at the cost of increased latency.

To better balance jitter, motion blur, and latency, the present application discloses various techniques for control of the illumination configuration employed by a display device for illuminating a display frame based on one or more parameters, including frame rate, user preferences, original equipment manufacturer (OEM) settings, hardware performance capabilities, current hardware state, image content, user gaze direction, and the like. Referring now to FIG. **2**, a taxonomy 200 of these various illumination control techniques, and various combinations thereof, are illustrated with reference to timing chart **130** of FIG. **1**. The illumination control techniques described herein can be generally categorized as: techniques for configuring the illumination level(s) and durations implemented within a frame period based on frame rate (hereinafter referred to as "frame rate-based illumination control techniques **202**; techniques for configuration the position of an illumination strobe within a frame period (hereinafter referred to as "strobe position control techniques **204**"); and techniques for controlling the illumination configuration on a region-by-region basis (hereinafter referred to as "regional illumination control techniques **206**").

In at least one embodiment, the backlighting level (for transmissive-type display devices) or the baseline illumination level (for emissive-type display devices) is varied over each frame period during the display of a sequence of frames in accordance with the "illumination configuration" for that frame period. As illustrated by timing chart **130** of FIG. **1**, the illumination configuration for a frame period includes, for example, the selective implementation of an illumination strobe **134**, selective implementation of a constant illumination level preceding the illumination strobe **134** (referred to herein as "front illumination fill" or simply "front fill"), and selective implementation of a constant illumination level following the illumination strobe **134** (referred to herein as "back illumination fill" or simply "back fill"), or a combination thereof. A front illumination fill **138** "fills" the portion of the frame period **102** preceding the illumination strobe **134** (that is, extends from the start of the frame period **102** to the start of the illumination strobe **134**). A back illumination fill **140** "fills" the portion of the frame period following the illumination strobe **134** (that is, extends from the end of the illumination strobe **134** to the end of the frame period **102**). Accordingly, in such instances, a frame rate-based illumination control technique **202** is employed to control whether the illumination strobe **134** is implemented for a given frame period, as well as the "output" of one or more of an implemented illumination strobe **134**, the front illumination fill **138**, and the back illumination fill **140**, based at least on the frame rate of the sequence of frames being displayed. As used herein, the "output" of an illumination strobe or illumination fill refers to the product of the illumination level and duration of the corresponding strobe or fill. Such techniques include, but are not limited to, a technique **208** for adjusting the illumination level or duration of strobe **134** relative to one or both of the front illumination fill **138** or the back illumination fill **140** based on frame rate, and a technique **210** for adjusting the front illumination fill **138** and the back illumination fill **140** relative to each other based on frame rate. These techniques are described in greater detail below with reference to FIGS. **9-13**.

In the event that an illumination strobe is to be implemented as part of the illumination configuration for a frame period, the position of the illumination strobe (e.g., position **136** of illumination strobe **134** of timing chart **130**, FIG. **1**) within the corresponding frame period can affect the display of a frame and the user's perception of the displayed frame. Accordingly, one or more strobe position control technique **204** can be implemented to more effectively position an illumination strobe within a frame period based on any of a variety of factors, such as frame rate, user preference, presence of a delayed VSYNC or next frame start, and the like. The strobe position control techniques **204** are described in greater detail below with reference to FIGS. **14** and **15**.

Further, in some embodiments the display device employs backlighting or a display matrix that has individually-controllable illumination regions, that is, can be controlled on a region-by-region basis. In such instances, a regional illumination control technique **206** can be employed to control the illumination configuration for each illumination region based on a variety of considerations. For example, a technique **212** for regional illumination control employs per-region brightness measurements or other brightness representations for a frame to be displayed to set a strobe-based illumination configuration for one or more illumination regions for the frame period corresponding to the frame. As another example, a technique **214** for regional illumination control employs motion estimation or other motion analysis to evaluate the motion of objects within each region of a frame associated with a corresponding illumination region of the display device and to set the illumination configuration for each illumination region when the frame is displayed. As yet another example, a technique **216** relies on a gaze tracking subsystem to identify a gaze location on the display matrix to identify which illumination region is a foveal region and which illumination regions are peripheral regions, and then setting the illumination configuration for each illumination region during display of a frame accordingly. Note that reference to "region", "regional", or "regionally", as used herein, in addition to referring to multiple regions, can also refer to a single global region for the entire display device, unless otherwise noted. Moreover, the per-region analysis described herein may be used to control the illumination of a different number of regions—that is, the number of regions analyzed may be greater than, less than, or equal to the number of regions having illumination control as a result of such analysis. These regional illumination control techniques **206** are described in greater detail below with reference to FIGS. **18-26**.

The techniques for illumination control described herein typically consider one or more factors, such as frame rate, in determining a corresponding illumination configuration for one or more frame periods. In some embodiments, the relationship between the input factors and the resulting parameters for the illumination configuration is a fixed relationship **218**, implemented as, for example, one or more look-up tables (LUTs), as a functional representation or algorithmic representation, and the like. In other embodiments, the relationship between the input factors and the resulting parameters for the illumination configuration is an adaptive relationship **220** that employs machine learning to dynamically adjust the relationship based on a modeling of the behavior of the display system. In still other embodiments, the relationship is a combination of a fixed relationship **218** and an adaptive relationship **220**. Whether fixed, adaptive, or a combination thereof, the relationship between input factors and output parameters for an illumination configuration for one or more frame periods can be set based on original equipment manufacturer (OEM) input or control **222**, based on user input or control **224**, set based on input or control from other users of similar systems, or a combination thereof, as described in greater detail below with reference to FIGS. **16** and **17**.

As represented by lines **228**, **230**, and **232**, control of the illumination configuration for a frame period is not limited to employment of only one technique or only techniques of the same type. To illustrate, in some embodiments one or more frame rate-based illumination control techniques **202** are employed individually or in combination with one or more regional illumination control techniques **206**, in combination with one or more strobe position control techniques **204**, or in combination with both one or more regional illumination control techniques **206** and one or more strobe position control techniques **204**. Similarly, in some embodiments one or more strobe position control techniques **204** are employed individually or in combination with one or more regional illumination control techniques **206**, or one or more regional illumination control techniques **206** are employed together.

Note that for ease of illustration, some of the illumination control techniques are described herein as involving the determination of an illumination configuration based on one or more aspects of a frame to be displayed and then implementing that illumination configuration for the frame period in which that same frame is to be displayed. However, it will be appreciated that due to the processing effort involved in determining an illumination configuration from one or more of such frames, the illumination configuration often will not be ready for implementation for display of the same frame(s) on which it was based. In such cases, the illumination configuration instead is employed for one or more subsequent frames, and the illumination configuration(s) determined from these subsequent frames are employed for one or more still further subsequent frames and so forth. As such, reference to application of an illumination configuration for display of the same frame from which the illumination configuration was determined should also be understood to similarly describe application of an illumination configuration for display of a subsequent frame, unless otherwise noted.

FIG. **3** illustrates an example display system **300** for implementing one or more of the illumination configuration control techniques described herein in accordance with some embodiments. The display system **300** includes a rendering device **302** and a display device **304** connected by a wired or wireless interconnect **305**. The rendering device **302** includes any of a variety of devices used to generate video content, including a notebook computer, a desktop computer, a server, a game console, a compute-enabled smartphone, and the like. The display device **304** includes a digital display device to display video content, such as a digital television, computer monitor, portable device display, and the like. Note that the rendering device **302** and the display device **304**, in some implementations, are implemented in the same device, such as in the case of a tablet computer, notebook computer, compute-enabled phone, and the like. The rendering device **302** includes at least one memory **306**, at least one processor, such as a GPU **308** and a central processing unit (CPU) **310**, and a display interface (IF) **312**. The display device **304** includes a display interface **314**, a display controller **316**, and a display matrix **318**. The display interfaces **312**, **314** include wired or wireless interconnect interfaces, such as HDMI interfaces, DisplayPort interfaces, embedded DisplayPort (eDP) interfaces, and the like. The display controller **316** is implemented as one or more processors to execute software instructions stored in memory (not shown), one or more programmable logic components, one or more hardcoded logic components, or a combination thereof. The display matrix **318** includes a two-dimensional array of pixels used to display a sequence of display images, and includes, for example, a light emitting diode (LED) matrix, an organic LED (OLED) matrix, a liquid crystal (LC) matrix, a matrix of movable mirrors for a digital light processing (DLP) display, or the like.

As a general operational overview, the memory **306** stores one or more sets of executable software instructions to manipulate the CPU **310** and GPU **308** to render a video stream including a series of display frames and corresponding metadata and to transmit this video stream to the display device **304** via the display interfaces **312**, **314** and the interconnect **305**. At the display device **304**, the display controller **316** receives each display frame and corresponding metadata in turn, and processes the display frame for display in sequence at the display matrix **318** during a corresponding frame period.

The display device **304** is implemented as, for example, an emissive-type display, a transmissive-type display, a reflective-type display, or a hybrid thereof. As illustrated by FIG. **4**, a transmissive-type display device **404** (one embodiment of the display device **304**) implements the display matrix **318** as an LC matrix **402** and a backlight **405** and the display controller **316** is implemented as an LC controller **406** and a backlight controller **408**. The LC matrix **402** implements an array of LC pixels **410**, with each LC pixel **410** composed of one or more LC subpixels representing a corresponding color (e.g., red, green, and blue) of the pixel. In operation, each row of pixel data of a frame is fed sequentially to the LC controller **406**, which selectively activates the LC pixels **410** at the corresponding row based on the pixel value for the corresponding pixel in that row (e.g., pixel(X,Y) being the pixel value for the frame at column X and row Y). The backlight **405** is composed of an array or other set of LEDs that are selectively activated to emit light which is then polarized and selectively transmitted through each LC pixel **410** of the LC matrix **402** based on the corresponding pixel value used to selectively activate the LC pixel **410**.

Thus, to "display" the frame, the backlight controller **408** uses one or more LED drivers **414** to drive the LEDs **412**, where the amount of current, voltage, or pulse shape (collectively, "power") driven by the LED drivers **414**, and thus the illumination intensity of the light emitted by the LEDs **412**, is controlled during each frame period via an illumination control (CTL) signal **416** controlled by the backlighting controller **408**. As such, as the level or value of the illumination CTL signal **416** varies over a frame period, the backlighting emitted by the LEDs **412** varies accordingly. As such, the illumination configuration for a frame period is implemented in the transmissive-type display device **404** through configuration of the level or value of the illumination CTL signal **416** by the backlighting controller **408**. That is, the backlighting controller **408** implements any front illumination fill, illumination strobe, and back illumination fill for a frame period through corresponding control of the illumination CTL signal **416**.

Turning to FIG. **5**, an emissive-type display device **504** (one embodiment of the display device **304**) implements the display matrix **318** as an LED matrix **502** and the display controller **316** is implemented as an LED controller **506**. The LED matrix **502** implements an array of pixels **510**, with each pixel **510** composed of one or more subpixels **512**, each representing a corresponding color (e.g., red, green, and blue) of the pixel. Each subpixel is implemented as an LED or an OLED. In operation, each row of pixel data of a frame is fed sequentially to the LED controller **506**, which selectively activates the subpixels **512** of the pixels **510** at the corresponding row based on the pixel value for the corresponding pixel in that row. Thus, to "display" the frame at the display device **504**, each subpixel **512** is driven by a corresponding driver **514**, where the power provided by the driver **514** to the subpixel **512**, and thus the illumination intensity of the light emitted by the subpixel **512**, is controlled by the combination of the associated subpixel value of the pixel represented by the subpixel **512** and the current illumination level of the illumination configuration for the frame period as represented by an illumination CTL signal **516**. In some embodiments, the subpixel value and the value of the illumination CTL signal **516** are multiplied to generate a resulting value that controls the magnitude of current, voltage, or pulse shape supplied by the driver **514**. As such, the illumination CTL signal **516**, representing the current illumination configuration value at the corresponding point in time in the frame period, acts to scale the illumination intensity of each subpixel up or down. For example, if the illumination CTL signal **516** is represented as an eight-bit value, then the illumination intensity of the subpixels **512** of the LED matrix **502** can be scaled up or down over 256 steps. Accordingly, the display device **504** implements any front illumination fill, illumination strobe, and back illumination fill for a frame period through corresponding control of the illumination CTL signal **516**.

Although FIGS. **4** and **5** illustrate embodiments of the display device **304** in which the illumination intensity is globally scaled up or down during a frame period in accordance with the same illumination configuration for all pixels of the frame, in other embodiments the display device **304** implements a regional illumination approach in which the display matrix **318** is partitioned into a plurality of individually-controllable illumination regions. That is, each illumination region is separately controllable so as to implement a region-specific illumination configuration during a frame period. As illustrated by FIG. **6**, this partitioning is implemented in any of a variety of ways. Global partitioning **602** illustrates a configuration in which there is no partitioning; that is, the entire display matrix **318** is a single, or global, illumination region **604**. Row partitioning **612** illustrates a configuration of the display device **304** in which the display matrix **318** is partitioned by row such that each subset of one or more rows of the display matrix **318** is organized as a separate illumination region **614**. Conversely, column partitioning **622** illustrates a configuration of the display device **304** in which the display matrix **318** is partitioned by column such that each subset of one or more columns of the display matrix **318** is organized as a separate illumination region **624**. Grid partitioning **632** illustrates a configuration of the display device **304** in which the display matrix **318** is partitioned by row and by column such that the pixels are partitioned into a plurality of illumination regions **634**, each region including pixels from one or more rows and one or more columns. Other partitioning schemes can be employed to divide the display matrix **318** into illumination regions that can be separately controlled for illumination intensity purposes.

FIG. **7** illustrates the software stacks implemented at the rendering device **302** and the display device **304** to facilitate implementation of one or more illumination configuration control techniques in accordance with some embodiments. Software stack **702** is implemented in the rendering device **302**, and includes one or more video content applications **704**, one or more operating system (OS) interfaces **706**, a software developer kit (SDK)/OS interface **708**, a graphics driver **710**, and a display driver **712**. The video content application **704** includes a software application that sources the video content to be rendered, such as a gaming application, a virtual reality (VR) or augmented reality (AR) application, a video playback application, and the like. Drawing instructions for a display image of this video content are provided to the graphics driver **710** via the OS interface **706**, whereupon the graphics driver **710** coordinates with the GPU **308** to render the corresponding display frame, which is buffered in a frame buffer or other storage component of the rendering device **302**. The display driver **712** then operates to transmit the pixel data representative of the buffered frame on a row-by-row basis, along with associated metadata, to the display device **304** via the interconnect **305**.

In some embodiments, control of the illumination configuration for one or more frame periods is primarily implemented by the rendering device **302**. In such embodiments, the software stack **702** includes a source-side illumination control module **714** to implement one or more of the illumination configuration control techniques described herein. In the example of FIG. **7**, the source-side illumination control module **714** is shown as part of the graphics driver **710**, but in other embodiments is implemented elsewhere in the software stack **702**. In these embodiments, the source-side illumination control module **714** determines an illumination configuration to implement for a corresponding set of one or more frames and transmits a representation of this illumination configuration to the display device **304** via, for example, a sideband transmission or as part of the metadata accompanying the pixel data of the frame. A display-side illumination control module **716** of a software stack **716** of the display device **304** receives this transmitted representation of the illumination configuration and then configures the display controller **316** to implement the illumination level(s) and segment durations represented by the illumination configuration during the corresponding frame period. In other embodiments, control of the illumination configuration for frame periods is primarily implemented at the display device **304** itself, in which case the display-side illumination control module **716** determines and implements an illumination configuration directly at the display device based on the frame data being received from the rendering device **302**.

Further, in some implementations, control of the illumination configuration can be controlled or modified through user input. In some embodiments, this user input is received at the rendering device **302**, and thus the software stack **702** includes a graphical user interface (GUI) **720** or other user interface to receive user input pertaining to illumination configuration and implement the user input accordingly. The GUI **720** can be implemented, for example, as part of the graphics driver **710** or, alternatively, as part of the video content application **704** or other software module of the software stack **702**. In other embodiments in which the display device **304** controls the setting of the illumination configuration, user input is received and implemented at a GUI **724** of the software stack **716** of the display device **304**.

FIG. **8** illustrates a method **800** representing the general process employed by the frame rate-based illumination output control techniques **202** (FIG. **2**) in accordance with some embodiments. For ease of illustration, method **800** is described in an implementation context in which the source-side illumination control module **714** (FIG. **7**) is responsible for determining the illumination configuration settings to be implemented. However, the process described below can be adapted for implementation by the display-side illumination control module **718** using the guidelines provided herein.

At block **802**, the GPU **308** renders or otherwise generates a frame in a sequence of frames at the direction of the video content application **704** and buffers the generated frame in a frame buffer or other storage component at the rendering device **302**. The display driver **712** then transmits the buffered pixel data and metadata representative of the generated frame on a row-by-row basis to the display device **304** via the interconnect **305**. At block **804**, for each row of pixel data received for the frame being transmitted, the display controller **316** configures each row of pixels of the display matrix **318** to represent the corresponding pixel values of the received row of pixel data so that when illumination of the frame at the display device **304** occurs during the associated frame period, display light representative of the frame is emitted by the display matrix **318**, either directly via LED, OLED, plasma, or other emissive pixel configurations, via selective backlight transmission by LC or other transmissive pixel configurations, or via selective light reflection by digital light processing (DLP) or other reflective pixel configurations.

In parallel with the rendering, transmission, and pre-display matrix configuration process of blocks **802** and **804**, the source-side illumination control module **714** determines the parameters of the illumination configuration to be used for displaying the subject frame. This sub-process begins at block **806** with the illumination control module **714** determining the current frame rate of the sequence of frames being generated. In some embodiments, the frame rate is fixed and represented by some control setting that is accessed or referenced by the illumination control module **714**. In other embodiments, the display system **300** employs a variable frame rate, in which case the illumination control module **714** monitors the frame periods of one or more preceding displayed frames (as specified by a software-based or physical VSYNC signal or a "frame completed" signal) to estimate the current frame rate, or receives from the GPU **308** an indication of the current frame rate being implemented by the GPU **308**. From this, the illumination control module **714** estimates the duration of the next frame period via, for example, linear extrapolation, a polynomial best fit analysis, Kalman filtering, a machine learning process, and the like.

Based on the current frame rate, at block **808** the illumination control module **714** determines whether the illumination configuration for displaying the frame is to include an illumination strobe, and if so, at least one of the illumination level or duration to be used for the illumination strobe. Concurrently, at block **810** the illumination control module **714** determines what illumination level(s) are to be implemented for the front illumination fill and back illumination fill for the illumination configuration. The processes of blocks **808** and **810** is described in greater detail below with reference to FIGS. **9-13**.

With the illumination configuration determined, the illumination control module **714** transmits a representation of the illumination configuration to the display device **304**. This representation of the illumination level(s), durations, and positions of the illumination configuration can be implemented in any of a variety of formats and transmitted to the display device **304** in any of a variety of ways, including as metadata or sideband data. To illustrate, assuming the display device **304** is configurable to provide an illumination configuration having a non-zero front illumination fill, an illumination strobe, and a non-zero back illumination fill with fixed segment positions and durations, the illumination configuration can be represented as a control data structure having three values, with a first value representing the illumination level for the illumination strobe, a second value representing the illumination level for the front illumination fill, and a third value representing the illumination level for the back illumination fill. In other embodiments with variable position and duration of the illumination strobe, the widths of at least two of the segments is transmitted, and thus allowing derivation of the width and position of the third segment in instances where the frame period is fixed or known. In other embodiments, the display controller **316** includes a pre-populated table configured with different combinations of front illumination fill levels, back illumination fill levels, and strobe illumination levels, and the representation of the determined illumination configuration can include transmission of an index value representing a corresponding entry of the table at the display controller **316**.

In response to receiving the representation of the determined illumination configuration, at block **814** the display-side illumination control module **718** configures the display controller **316** to control the illumination level of the display matrix **318** over the course of the corresponding frame period so that the frame is illuminated by the display matrix **318** and the resulting display light projected to the user. For a transmissive-type display device (e.g., display device **404**, FIG. **4**), control of the illumination level of the display matrix **318** over the corresponding frame period is achieved by controlling the illumination intensity, or light output, of the backlight **405** to reflect the illumination level of the illumination configuration at the corresponding point in time within the frame period. Reflective-type display devices are controlled in a similar manner by controlling the illumination level of the reflected light source. For emissive-type display devices (e.g., display device **504**, FIG. **5**), control of the illumination level of the display matrix **318** over the corresponding frame period is achieved by scaling each subpixel value based on an illumination control value that represents the illumination level of the illumination configuration at the corresponding point in time within the frame period so that the current, voltage, pulse shape, or other power driving the LED, OLED, or other emissive pixel scales with the illumination level within the illumination configuration. That is, the power used to drive the emissive pixel is, in effect, representative of a product of the subpixel value for that emissive pixel and a value representing the current illumination level in the illumination configuration at that point in time in the frame period.

The flow of method **800** then returns to block **802** for the generation, buffering, transmission, and pre-display configuration of the next frame. In some embodiments, the same illumination configuration is employed for each frame generated within a sequence of two or more frames (e.g., the sequence representing the frames generated between scene changes or the frames between two frames having substantially different brightness levels than their preceding frame), in which case the sub-process of blocks **806**, **808**, **810**, and **812** is only performed once per sequence of frames. In other embodiments, an illumination configuration is separately determined for each frame to be displayed, in which case the sub-process of blocks **806**, **810**, and **812** is performed anew for each generated frame.

Turning now to FIG. **9**, an example technique for implementing the illumination output determination processes of blocks **808** and **810** of method **800** is illustrated. In one embodiment, the illumination control module **714** implements a output determination module **900** to obtain various input parameters **902**, and from these input parameters **902**, generate a representation **904** of the illumination configuration (e.g., illumination configuration **906** or illumination configuration **908**) to be implemented for the illumination of a frame at the display device **304**.

The frequency at which successive frames are displayed, that is, the frame rate, typically is a primary factor in the manifestation of various display artifacts perceived by a user. At lower frame rates (e.g., at or below 60 frames-per-second (FPS)), most users are likely to perceive flicker caused by illumination strobes or other variations in the average illumination level between frames. At higher frame rates (e.g., at or above 100 FPS), the flicker is likely to become imperceptible, but the timing of an illumination strobe potentially will result in ghosting or tearing due to the row-by-row scan out and settling time of pixels of the display device. Further, higher frame rates can result in motion blur when constant illumination levels are used due to persistence of vision exhibited by most users. Accordingly, in at least one embodiment, the current frame rate (signal **910**) is employed as one of the input parameters **902** considered by the output determination module **900** in determining the illumination output(s) (that is, at least one of illumination level and duration) of the illumination configuration at issue.

User input (signal **912**) also can be employed by the output determination module **900**. To illustrate, the user may be less bothered by flicker, and thus provide user input indicating a lower threshold for employing an illumination strobe than would otherwise be set by the output determination module **900**. Conversely, another user may be more sensitive to flicker, and thus provide user input that sets a higher threshold for employing an illumination strobe. The use of user input as a factor in setting an illumination configuration is described in greater detail below with reference to FIG. **16**.

The output determination module **900**, in one embodiment, also utilizes one or more current operational parameters (signal **914**) of the display system **300** as input parameters **902** for determining the appropriate illumination levels of a resulting illumination configuration. Such current operational parameters include, for example, a level of ambient light (which in turn is suggestive of a target average brightness of the display device), a current temperature of the drivers for the backlight **405** or the LED matrix **502** (which is indicative of whether the drivers are at risk of being overloaded), a current operational state of the GPU **308** (which indicate, for example, whether the next frame period is to be delayed due to the GPU **308** being unable to render the corresponding frame in time), and the like.

In at least one embodiment, an illumination configuration is represented by at least three parameters: a strobe level value **916** representing an illumination level to employ for an illumination strobe (if activated) in the frame period, a front fill level value **918** representing an illumination level to employ for a front illumination fill preceding the illumination strobe, and a back fill level value **920** representing an illumination level to employ for a rear illumination fill following the illumination strobe. To illustrate, illumination configuration **906**, having no front illumination fill, an illumination strobe at illumination level X**1** and a back illumination fill at illumination X**2** could be represented by the tuple <0, X**1**, X**2**>, whereas illumination configuration **908**, having a front illumination fill **921** at illumination level X**3**, an illumination strobe **923** at illumination level X**5**, and a back illumination fill **925** at illumination level X**4** can be represented by the tuple <X**3**, X**5**, X**4**>.

As described below, the position of the illumination strobe can be adjusted, and thus the illumination configuration further can include one or more segment position parameters **927** that specify the position of one or more of the illumination strobe, the front illumination fill, and the back illumination fill within the frame period. The "position" of a corresponding segment is represented, for example, as a start time following start of the frame period and a width or other representation of duration of the segment. If the frame period is constant, then specification of the positions of any two of the illumination strobe, front illumination fill, and back illumination fill allows the position of the remaining unspecified segment to be calculated. In the event that an illumination strobe is not implemented in the illumination configuration, the strobe level value **916** is set to zero, or alternatively, is set to the same value as either the front fill level value **918** or the back fill level value **918**, thereby in effect extending the duration of the corresponding illumination fill. In other embodiments, the illumination level of an illumination strobe, if activated, is fixed or set, in which the representation **904** omits the strobe level value **916**, or includes, for example, a binary value to identify whether to include an illumination strobe in the illumination configuration. In other embodiments, the strobe duration also is adjustable based on frame rate or other input parameters **902**, in which case the representation **904** would also include a strobe duration value **915** representing the width or other duration representation of the illumination strobe (it will be appreciated that the strobe duration value **915** serves as a particular segment position parameter **927**).

The values **916**, **918**, and **920** are presentable in any of a variety of formats. In some embodiments, each value is an absolute value set between the minimum and maximum thresholds for the corresponding illumination level. For example, each value **916**, **918**, and **920** can be implemented as an eight-bit value, and thereby providing 256 illumination level steps each. In other embodiments, some or all of the values **916**, **918**, and **920** are relative values. For example, the values **918** and **920** can represent some percentage of the illumination value represented by the strobe level value **916**.

The output determination module **900**, in one embodiment, identifies the illumination level(s) to be employed, the strobe duration to be employed (in implementations with variable strobe durations), and the positions/durations of the strobe and front and back fills in an illumination configuration based on the input parameters **902** using any of a variety of mechanisms or combinations thereof. In some embodiments, the output determination module **900** maintains one or more LUTs **922** or other tables that represent the relationship between a value for one or more input parameters **902** and the corresponding illumination level(s), strobe duration, and segment position(s) to be implemented in the illumination configuration. To illustrate using a simple example based on frame rate and in which the duration or positions of the segments are fixed, the LUT **922** could be configured as shown in Table 1:

TABLE 1

example LUT implementation

FPS	Strobe level	Front fill level	Back fill level
<60	30	30	30
60-100	50	20	20
>100	70	0	40

Thus, a frame rate of below 60 FPS results in a constant illumination configuration (that is, the illumination level is constant over the entire frame period), a frame rate of 75 FPS would result in implementation of an illumination strobe at an illumination level of 50, a front illumination fill at an illumination level of 20, and a back illumination fill at an illumination level of 20, and a frame rate of 120 FPS would result in implementation of an illumination strobe at an illumination level of 70, a back illumination fill at an illumination level of 40, and no front illumination fill (that is to say, a front illumination fill at an illumination level of 0).

In other embodiments, the relationship between input parameter(s) **902** and illumination level(s) and segment positions of an illumination configuration is provided by one or more functions **924** or other functional algorithms implemented in software code. For example, the example relationship of the strobe level value **916** and FPS in Table 1 could instead be represented as a function **924** in the format of:

$$\text{Strobe\_level} = \begin{cases} 30, & FPS < 60 \\ 50, & 60 \le FPS \le 100 \\ 70, & FPS > 100 \end{cases}$$

In still other embodiments, the relationship between input parameter(s) **902** and illumination level(s)/positions/durations of an illumination configuration is provided using a learned model **926** developed using a neural network or other machine learning (ML) technique. To illustrate, in some embodiments, the user is presented with test video displayed using different illumination configurations and the user's feedback on the performance of each test video used as a training set for initial training of the learned model **926**. Thereafter, the learned model can be further refined based on user input that adjusts various illumination configuration parameters to better suit the user's particular preferences, based on observations of correlations between frame rates or other various operational parameters and the effectiveness of the display of frames using the resulting illumination configurations, and the like.

The relationship between one or more operational parameters **902** and corresponding illumination level(s), durations, and positions of the illumination configuration are configured in any of a number of manners. In some embodiments, the relationship is predefined by an OEM or supplier of the graphics driver **710** or the GPU **308**, and thus can be periodically updated using firmware or software updates. For example, a graphics driver update release can include updated values for the LUT **922**. Further, in some embodiments, user input is used to originally create the representation of the relationship, or to adjust previously-determined values. For example, using the GUI **720** (FIGS. **7** and **16**), the user can set the FPS thresholds used to change illumination level(s), to activate or deactivate use of an illumination strobe, to change the illumination level(s) themselves, and the like. Still further, as mentioned above, the relationship can be a dynamic relationship as represented by, for example, a learned model that is continuously updated based on various training inputs.

Referring now to FIGS. **10** and **11**, more detailed example relationships between frame rate (as an input parameter **902**) and the illumination parameters employed for an illumination configuration is shown. FIG. **10** depicts two charts, chart **1000-1** and **1000-2**, that illustrate specified relationships between use and level/duration of an illumination strobe and a corresponding level of a surrounding fill based on frame rate, so as to achieve a more suitable balance between flicker mitigation and motion blur mitigation than typically possible using only constant level illumination or strobe-only illumination. This specified relationship, in some instances, is generalized as increasing the output of an illumination strobe and decreasing the magnitude of illumination fill as frame rate increases, and vice versa. With this approach, reduced or eliminated strobe emphasis at lower frame rates mitigates the potential for perceptible flicker, while increased strobe emphasis and decreased fill emphasis at higher frame rates mitigates the potential for image ghosting and motion blur.

In the chart **1000-1**, frame rate is represented by the abscissa, the left-side ordinate represents illumination level for both a strobe and a surrounding fill, and the right-side ordinate represents the duration for the strobe (fixed in this example). Line **1002** represents the strobe illumination level that varies between 0 and a maximum illumination level STRB_MAX1 based on frame rate. Line **1004** represents the illumination fill level that varies between 0 and a maximum illumination fill level FILL_MAX based on frame rate, where the surrounding fill level represents an illumination fill that both precedes and follows any illumination strobe present, or represents a constant illumination level in the absence of an illumination strobe. Line **1006** represents the duration, or width, of the illumination strobe, which in this example is fixed at WIDTH_C (e.g., 4 ms) in this example once an illumination strobe is activated (at frame rate F_LOW). The left-side ordinate represents the scale of the illumination level for the surrounding fill level, whereas the right-side ordinate represents the scale of the illumination level for the illumination strobe, when present.

As illustrated by lines **1002** and **1004**, between a frame rate of 0 and F_LOW (e.g., 80 FPS), the illumination configuration relies entirely on the surrounding fill to provide the illumination, with a constant fill illumination level of FILL_MAX. At a frame rate F_LOW, an illumination strobe is activated, with the strobe having a fixed duration of WIDTH_C (as illustrated by line **1006**). Thus, between frame rate F_LOW and F_HIGH (e.g., 120 FPS), the strobe illumination level increases (substantially linearly in this example) while the illumination level of the illumination fill reduces (non-linearly in this example) from the level FILL_MAX to zero. Thereafter, illumination is provided solely by the illumination strobe for frame rates between F_HIGH and F_MAX, with the strobe illumination level decreasing (non-linearly in this example) to compensate for the increasing strobe rate (due to increasing frame rate) so as to maintain a substantially constant illumination level. For each stage, the relationship between fill level, strobe level, and strobe duration is configured so as to maintain a substantially constant illumination level, regardless of frame rate. Thus, as illustrated by the stage between frame rate F_LOW and F_HIGH, as the strobe illumination level increases the fill illumination level decreases so that the overall illumination output is constant. Likewise, between frame rate F_HIGH and F_MAX, while the illumination strobe is the only illumination source, the illumination level of the strobe decreases with increase in frame rate in view of the increased number of strobes per second so as to maintain a constant illumination per unit time.

Turning to chart **1000-2**, in this chart frame rate is represented by the abscissa, the left-side ordinate represents illumination level for both a strobe and a surrounding fill, and the right-side ordinate represents the duration for the strobe (variable in this example). Line **1012** represents the strobe illumination level that varies between 0 and a maximum illumination level STRB_MAX2 based on frame rate. Line **1014** represents the illumination fill level that varies between 0 and the maximum illumination fill level FILL_MAX based on frame rate, where the surrounding fill level represents an illumination fill that both precedes and follows any illumination strobe present, or represents a constant illumination level in the absence of an illumination strobe. Line **1016** represents the duration, or width, of the illumination strobe, which in this example varies based on frame rate up to a maximum duration WIDTH_MAX once an illumination strobe is activated (at frame rate F_LOW). The left-side ordinate represents the scale of the illumination level for the surrounding fill level, whereas the right-side ordinate represents the scale of the illumination level for the illumination strobe, when present.

As illustrated by lines **1012** and **1014**, between a frame rate of 0 and F_LOW, the illumination configuration relies entirely on the surrounding fill to provide the illumination, with a constant fill illumination level of FILL_MAX. At a frame rate F_LOW, an illumination strobe is activated, with the strobe having a variable duration based on frame rate (as illustrated by line **1014**). Thus, between frame rate F_LOW and F_HIGH, both the strobe illumination level and the strobe duration increases (substantially linearly in this example) while the illumination level of the illumination fill reduces (non-linearly in this example) from the level FILL_MAX to zero. Thereafter, illumination is provided solely by the illumination strobe for frame rates between F_HIGH and F_MAX, with the strobe duration constant at WIDTH_MAX and the strobe illumination level decreasing (non-linearly in this example) to compensate for the increasing strobe rate (due to increasing frame rate) so as to maintain a substantially constant illumination level. As with the relationships represented by chart **1000-1**, the relationships between fill level, strobe level, and strobe duration represented in chart **1000-2** is configured so as to maintain a substantially constant illumination level, regardless of frame rate. Thus, as illustrated by the stage between frame rate F_LOW and F_HIGH, as the strobe output increases the fill illumination output decreases so that the overall illumination output is constant. Likewise, between frame rate F_HIGH and F_MAX, while the illumination strobe is the only illumination source, the illumination level of the strobe decreases (at a constant strobe duration) with increase in frame rate in view of the increased number of strobes per second so as to maintain a constant illumination per unit time.

FIG. **11** illustrates various example illumination configurations resulting from the relationship represented by chart **1000-1** of FIG. **10** at different frame rates. Timing chart **1100** illustrates a sequence of two frame periods **1102-1** and **1102-2** used as a reference for the respective timings of the illustrated illumination configurations. Note that the duration of the frame periods **1102-1** and **1102-2** are inversely proportional to the frame rate being referenced in the corresponding illumination configuration.

Illumination configuration **1104** represents an illumination configuration determined from chart **1000-1** at a frame rate F**1** that is below the threshold frame rate F_LOW defining the lowest frame rate at which an illumination strobe is implemented (around 50 FPS, for example). Thus, as determined by the values of lines **1002** and **1004** at frame rate F**1**, for the illumination configuration **1104** the surrounding fill level is set to the maximum fill level FILL_MAX and the strobe illumination level is set to STROBE_MIN (e.g., 0), resulting in the illumination configuration **1104** having a constant illumination level **1106** across each of the frame periods **1102-1** and **1102-2**. Displaying a sequence of frames at the frame rate F1 using this illumination configuration thus exhibits reduced or eliminated flicker as there is no strobe present.

Illumination configuration **1108** represents an illumination configuration determined from chart **1000-1** at a frame rate F2 that is above the threshold frame rate F_LOW but below a threshold frame rate F_HIGH at which the illumination strobe serves as the primary source of illumination during the frame period. In the example of chart **1000-1**, the strobe illumination level increases as frame rate increases from F_LOW to F_HIGH as illustrated by the corresponding increasing segment of line **1002** (recall again that in this example, strobe duration is constant regardless of frame rate starting at frame rate F_LOW), while the surrounding fill illumination level decreases as frame rate increases from F_LOW to F_HIGH as illustrated by the corresponding decreasing segment of line **1004**. Thus, as frame rate increases in this range, the strobe illumination level increases and the surrounding fill illumination level decreases commensurately. Accordingly, at the frame rate F**2**, the resulting illumination configuration **1108** includes a surrounding fill **1110** having an illumination level Y**2** (<FILL_MAX) and an illumination strobe **1112** having an illumination level Y**3**. Thus, at the middle frame rates, including frame rate F**2**, the illumination configuration employs a balanced blend of strobe magnitude and fill magnitude, and thus achieving the reduced motion-blur benefit of employing an illumination strobe while also reducing the impact of flicker caused by the illumination strobe by surrounding the strobe with fill illumination, and thus reducing the net difference in illumination level change caused by the illumination strobe. Moreover, by using a moderate level of fill in the frame periods **1102-1** and **1102-2**, a given average illumination for the frame periods is achievable with a lower-level illumination strobe, and thus requiring a lower transient current or other power output from the drivers of the backlight sources or emissive light pixels to implement the strobe, and enabling longer life for light sources such as OLED that degrade over time at stronger drive levels.

Illumination configuration **1114** represents an illumination configuration determined from chart **1000-1** at a frame rate F**3** that is above the threshold frame rate F_HIGH at which the illumination strobe serves as the primary source of illumination during the frame period. In the example of chart **1000-1**, the strobe illumination level reaches its maximum level STROBE_MAX1 at F_HIGH and then decreases for all frame rates above F_HIGH as illustrated by the corresponding downward sloped segment of line **1002** so as to maintain a substantially constant illumination per unit time, while the surrounding fill illumination level reaches its lowest illumination level FILL_MIN at frame rate F_HIGH. Thus, as frame rate increases in this range, the strobe illumination level gradually decreases with frame rate so as to maintain a constant illumination level in view of the increased frame rates (and thus increased strobe rate). Accordingly, at the frame rate F**3**, the resulting illumination configuration **1114** includes a surrounding fill **1116** having an illumination level FILL_MIN (<Y**2**) and an illumination strobe **1118** having an illumination level Y**4** (>Y**3**). Thus, at higher frame rates (e.g., 100 FPS or above), including frame rate F**3**, the illumination configuration emphasizes use of an illumination strobe to reduce or elimination motion blur and deemphasizes surrounding fill as any flicker caused by the magnitude of change in illumination level between the surrounding fill and the strobe is unlikely to be detectable by the typical user at such frame rates. Moreover, as with illumination configuration **1108**, by using a non-zero level of fill in the frame periods **1102-1** and **1102-2**, the illumination configuration **1114** can provide a given average illumination for the frame periods with a lower-level illumination strobe, which requires a lower transient current or voltage from the drivers of the backlight sources or emissive light pixels to implement the strobe. However, in implementations in which the drive current at maximum strobe levels is not likely to substantially reduce the operational lifetime of the drivers or the light sources, the illumination configuration at the highest frame rates can, for example, employ illumination strobes only (that is, set all surrounding fill levels to zero).

As chart **1000-1** and the illumination configurations **1104**, **1108**, and **1114** illustrate, in the illustrated representation between frame rate and illumination levels, the corresponding illumination configuration switches from a constant illumination level configuration at lower frame rates, to a blended balance of illumination strobe to illumination fill at intermediate frame rates (with the balance tilting toward the illumination strobe as frame rate increase), to an illumination strobe-dominant configuration at the highest frame rates. In this manner, the illumination configuration can be tailored to address the visual artifacts more likely to appear at a given frame rate.

FIGS. **12** and **13** illustrate another more detailed example relationship between frame rate (as an input parameter **902**, FIG. **9**) and the illumination levels employed for an illumination configuration is shown. The chart **1200** of FIG. **12** represents a relationship between frame rate (abscissa), a strobe illumination level (line **1202**), a front fill illumination level (line **1204**), and a back fill illumination level (line **1206**). The left-side ordinate represents the scale of the illumination level for the front and back fill illumination levels, whereas the right-side ordinate represents the scale of the illumination level for an illumination strobe, when present. In this example, the strobe duration is fixed for ease of illustration, and thus the strobe output is varied based on variation of the strobe illumination level.

Chart **1200** represents an example implementation of a specified relationship between use and level of an illumination strobe and corresponding levels of front and back illumination fills based on frame rate so as to achieve a more suitable balance between flicker mitigation and motion blur mitigation than typically possible using only constant level illumination or strobe-only illumination. This specified relationship can be generalized as increasing the magnitude of an illumination strobe and decreasing the magnitude of illumination fill as frame rate increases, and vice versa. With this approach, reduced or eliminated strobe emphasis at lower frame rates mitigates the potential for perceptible flicker, while increased strobe emphasis and decreased fill emphasis at higher frame rates mitigates the potential for image ghosting and motion blur. Moreover, with respect to the front and back illumination fills, the represented relationship further can be generalized as reducing the front illumination fill level relative to the back illumination fill level as frame rate increases.

FIG. **13** illustrates various example illumination configurations resulting from the relationship represented by chart **1200** of FIG. **12** at different frame rates. Timing chart **1300** illustrates a sequence of two frame periods **1302-1** and **1302-2** used as a reference for the respective timings of the illustrated illumination configurations. Note that the duration of the frame periods **1302-1** and **1302-2** are inversely proportional to the frame rate being referenced in the corresponding illumination configuration.

Illumination configuration **1304** represents an illumination configuration determined from chart **1300** at a frame rate F**1** that is below the threshold frame rate F_LOW defining the lowest frame rate at which an illumination strobe is implemented (around 50 FPS, for example). Thus, as determined by the values of lines **1202**, **1204**, and **1206** at frame rate F**1**, for the illumination configuration **1304** the front fill level and the back fill level both are set to the maximum fill level FILL_MAX and the strobe illumination level is set to STROBE_MIN (e.g., 0), resulting in the illumination configuration **1304** having a constant illumination level **1306** across each of the frame periods **1302-1** and **1302-2**. Displaying a sequence of frames at the frame rate F**1** using this illumination configuration thus exhibits reduced or eliminated flicker as there is no strobe present, and typically does not suffer from significant motion blur as motion blur is generally not readily detectable by the typical user as such low frame rates as motion judder typically is a more prominent issue at lower frame rates.

Illumination configuration **1308** represents an illumination configuration determined from chart **1200** at a frame rate F2 that is above the threshold frame rate F_LOW but below a threshold frame rate F_HIGH at which the illumination strobe serves as the primary source of illumination during the frame period. In the example of chart **1200**, the strobe illumination level increases as frame rate increases from F_LOW to F_HIGH as illustrated by the corresponding increasing sloped segment of line **1202**, while the front and back fill illumination levels decrease as frame rate increases from F_LOW to F_HIGH as illustrated by the corresponding decreasing sloped segments of line **1204** and **1206**. Thus, as frame rate increases in this range, the strobe illumination level increases and the surrounding fill illumination level decreases proportionally. However, as also illustrated by chart **1200**, the front fill level decreases at a greater rate than the back fill level as frame rate increases between the two thresholds F_LOW and F_HIGH, and thus resulting in the front illumination fill being deemphasized at a greater rate than the back illumination fill as frame rate increases. Accordingly, at the frame rate F**2**, the resulting illumination configuration **1308** includes a front illumination fill **1310** having an illumination level Y**1** (<FILL_MAX), a back illumination fill **1312** having an illumination level Y**2** (>Y**1**) and an illumination strobe **1314** positioned in between and having an illumination level Y**3** (>Y**2**). Thus, at the middle frame rates, including frame rate F**2**, a resulting illumination configuration employs a balanced blend of strobe magnitude and fill magnitude, and thus achieving the reduced motion-blur benefit of employing an illumination strobe while also reducing the impact of flicker caused by the illumination strobe by surrounding the strobe with fill illumination, and thus reducing the net difference in illumination level change caused by the illumination strobe.

As described in more detail below, the row-by-row scan out of a frame to the display device and the setup times to configure each pixel to reflect the pixel data being scanned in (particularly for LC-based pixels) often results in the lower rows of pixels of the display matrix **318** not yet being fully configured to reflect the current frame being input (and instead representing corresponding pixels from the previous frame scanned in or a transitional state) in the early part of the frame period used to display the frame being scanned in. As such, illumination during this early part of the frame period can result in display of a blended image composed of the upper pixel rows of the current frame and the lower pixel rows of the previous frame—a phenomenon known as screen tearing. The potential for screen tearing increases with frame rate as the frame period shrinks relative to the scan in and setup time for a frame. Thus, by implementing a frame rate-fill illumination output relationship that increases the difference between the back illumination fill and the front illumination fill as frame rate increases between the frame rate thresholds F_LOW and F_HIGH, less illumination is generated during the early part of the frame period as frame rate increases, and thus reducing the impact of any inadvertent illumination of a blended frame during the early part of the frame period, while more illumination is generated during the latter part of the frame period as frame rate increases, and thus increasing the proportion of display light representing the display matrix **318** after all rows of pixels of the current frame have been scanned in and have time to settle. Thus, as frame rate increases and with it the risk of screen tearing and ghosting, the influence of display light generated in the early part of a frame period is decreased and the influence of display light generated in the later part of the frame period is increased, thereby scaling the screen-tearing/ghosting mitigation as risk of screen tearing/ghosting increases. This visibility of screen tearing also can be further decreased by extending the illumination fill **1310** and delaying the illumination strobe **1314** and illumination fill **1312** until the scan out of the new pixels in the frame represented by frame period **1302-1** has completed, although such delays would add latency in exchange for reduced screen tearing.

Illumination configuration **1316** represents an illumination configuration determined from chart **1200** at a frame rate F**3** that is above the threshold frame rate F_HIGH at which the illumination strobe serves as the primary source of illumination during the frame period. In the example of chart **1200**, the strobe illumination level reaches its maximum level STROBE_MAX at F_HIGH and then declines for all frame rates above F_HIGH as illustrated by the corresponding declining segment of line **1202**, while the front fill level declines (at a greater rate) for all frame rates above F_HIGH to F_FILL_MIN at frame rate F_MAX as illustrated by the corresponding declining segment of line **1204**. Similarly, the back fill level continues to decline at a greater rate until it reaches the minimum level B_FILL_MIN at frame rate F_MAX. Thus, as frame rate increases in this range, at least one of the strobe illumination level, the front fill level or the back fill level declines to maintain constant illumination. Accordingly, at the frame rate F**3**, the resulting illumination configuration **1316** includes a front illumination fill **1318** having an illumination level Y**4** (<Y1), a back illumination fill **1320** having an illumination level Y**5** (<Y2) and an illumination strobe **1322** having an illumination level Y**6** (<=STROBE_MAX). Thus, at higher frame rates (e.g., 120 FPS or above), including frame rate F**3**, the illumination configuration emphasizes use of an illumination strobe to reduce or elimination motion blur and deemphasizes surrounding fill as any flicker caused by the magnitude of change in illumination level between the surrounding fill and the strobe is unlikely to be detectable by the typical user at such frame rates. Moreover, as with illumination configuration **1108**, by using a non-zero level of fill in the frame periods **1102-1** and **1102-2**, the illumination configuration **1114** can provide a given average illumination for the frame periods with a lower-level illumination strobe, which requires a lower transient current from the drivers of the backlight sources or emissive light pixels to implement the strobe. Further, as described above, the deemphasis of front illumination fill in favor of back illumination fill at these highest frame rates reduces the impact of any screen tearing potentially likely to occur at such high frame rates.

It should be noted that although charts **1000** and **1200** illustrate examples in which there are piecewise substantially linear relationships between frame rate and corresponding strobe and fill illumination levels for an illumination configuration for ease of description, in other embodiments these relationships are non-linear, piecewise or otherwise. Further, rather than having only two frame rate thresholds and a constant slope therebetween, the relationship between frame rate and a corresponding illumination level can have more than two inflection points.

FIGS. **14** and **15** together illustrate the general process employed by the strobe position control techniques **204** (FIG. **2**) in accordance with some embodiments. In at least one embodiment, this process can be implemented as an extension of method **800** in which the strobe position is determined in parallel with the strobe output determination process of block **808**, and is described below in this context. Moreover, this process is described in an implementation context in which the source-side illumination control module **714** (FIG. **7**) is responsible for determining the illumination configuration settings to be implemented. However, the process described below can be adapted for implementation by the display-side illumination control module **718** using the guidelines provided herein.

Turning to FIG. **14**, timing chart **1400** illustrates a sequence of two frame periods **1402-1** and **1402-2** used as a reference for the respective timings of the illustrated strobe positioning process. As described above, at the start of a frame period **1402** (signaled by, for example, assertion of a VYSNC OR VBI), the pixel data for the frame to be displayed during the frame period is scanned out of the frame buffer on a row-by-row basis and transmitted to the display device (as represented by scan out line **1406**), whereupon the display device **304** configures a corresponding row of the display matrix **318** based on the pixel data of the row of the frame currently being scanned in. The scan in of pixel data at each row is not instantaneous, but rather requires some time for the circuit elements representing the pixel to transition from a first state representing the corresponding pixel from the previous frame to a second state representing the corresponding pixel from the current frame. This transition is particularly long, relatively, for LCD displays due to the time needed for the LCs of the pixels to change state.

In timing chart **1400**, time T**1** represents the point in time in the frame period **1402-1** at which all rows of pixels for the current frame have been scanned in and the last row of pixels has settled to their new states. The duration from frame period start to time T**1** is relatively independent of frame rate, that is, it typically takes approximately the same amount of time to fully scan in a frame into the display matrix **318** regardless of the rate at which frames are transmitted when using a variable frame rate technique such as the Radeon™ FreeSync™ technology available from Advanced Micro Devices, Inc. (otherwise the scan out time is usually extended to fill the frame time by using a lower pixel transfer rate). Thus, as frame rate increases (and frame period duration decreases), the time needed to scan in a frame and allow sufficient settling occupies an increasingly larger proportion of the frame period duration.

The position of an illumination strobe in the illumination configuration for a frame period has implications for display quality in view of the scan in and settling process. Starting an illumination strobe earlier in the frame period can reduce latency, but risks introducing screen tearing if the illumination strobe is activated before scan in and settling have completed for the current frame. To illustrate, illumination configuration **1408** implements an illumination strobe **1410** that is positioned to start at time T**0** (<T1), and thus start when approximately the lower 40% of the rows of the current frame have not yet scanned in and settled. Accordingly, the illumination strobe **1410** will result in illumination of a hybrid frame which has approximately 60% of the upper rows of the current frame and approximately 40% of the lower rows of the previous frame (or some transitional states between the lower rows of the previous frame and the lower rows of the current frame). To avoid such artifacts, as

illustrated by illumination configuration **1412**, an illumination strobe **1414** instead is positioned closer to the end of the frame period, such as at time T**2** (>T**1**). This allows the full frame to be scanned in and settled before initiating the illumination strobe, but introduces latency. Moreover, if the display device **304** implements variable frame rates and if the next frame period starts early, the illumination strobe could not actually activate during the current frame period, but instead shift too far into the early part of the next frame period, thereby causing failure to display the current frame and likely screen tearing for the next frame.

To achieve a suitable balance between risk of screen tearing of a too-early illumination strobe and the latency and potential skipped frame display of a too-late illumination strobe, as illustrated by illumination configuration **1416**, the strobe position control technique **204** seeks to determine an appropriate position T(X) for the illumination strobe **1418** to be implemented in the illumination configuration **1416** that reduces or eliminates overlap with the scan out and settling period of the current frame while also reducing or eliminating the latency introduced by an overly-delayed strobe or skipped frame resulting from a strobe that is not positioned to activate before the start of the next frame period.

The strobe position control technique **204** is implemented separately or in conjunction with the frame rate-based illumination control technique **202** to set an illumination configuration. For example, in some implementations, the display system **300** uses either a constant fill configuration or a strobe-only configuration, depending on frame rate. When in a strobe-only configuration, the strobe position control technique **204** can be implemented to suitably position the strobe within the frame period. In other implementations, the display system uses a varying fill level and varying strobe output based on frame rate, in which case the strobe position control technique **204** can be used to position the strobe in the frame period along with one or both of a front illumination fill and a back illumination fill. However, it will be appreciated that the position of the illumination strobe defines the duration of both the front illumination fill and the back illumination fill, and thus the illumination levels set for the front and back illumination fills typically will be adjusted based on the duration of each fill in view of the strobe position that the average brightness of the frame period does not change depending on strobe position.

FIG. **15** illustrates a strobe positioning module **1500** that implements the strobe position control technique **204** so as to determine a suitable strobe position in accordance with some embodiments. The strobe positioning module **1500** receives one or more input parameters **1502**, and from these, generate a representation **1504** of the position of an illumination strobe in the illumination configuration to be implemented for the illumination of the frame at issue at the display device **304**. For purposes of description, the position of the illumination strobe is described as position within the frame period that the illumination strobe starts, or is activated. However, in other implementations, the position refers to a position of a middle of the illumination strobe or a position of an end of the illumination strobe. The representation **1504** of the strobe position can be expressed as a value that represents an absolute timing reference, such as a particular number of milliseconds or clock cycles from the start of a frame period, or an absolute timing reference, such as a particular percentage of the overall frame period (e.g., a value of <0.25> indicating that the illumination strobe should be initiated 25% of the way into a frame period). In at least one embodiment, the representation **1504** of the strobe position is included with the other parameter values of the representation of an illumination configuration transmitted to the display device **304** (or determined at the display device **304** itself). For example, a representation of an illumination configuration can be provided as metadata or sideband data in the form of a tuple with the format: <[strobe position], [strobe duration], [strobe level], [front fill level], [back fill level]>.

In one embodiment, the strobe positioning module **1500** utilizes one or more current operational parameters (signal **1506**) of the display system **300** as input parameters **1502** for determining the appropriate strobe position in the corresponding illumination configuration. In particular, such operational parameters are representative of a current loading of the rendering device **302** and thus useful in predicting whether the next frame period will start early, late, or on time. For example, the current operating parameters can include a representation of a power state, representation of the complexity of the current frame being rendered or the next frame to be rendered, or other indicator of the current loading of the GPU **308**, and thus indicate a probability as to the timing of the rendering and transmission of the next frame.

As explained above, the frame period is inversely proportional to the frame period, and as the scan in and settle time of a frame is relatively constant regardless of frame rate, and thus suitable timing of the position of the strobe within an illumination configuration becomes more pernicious with the increase in frame rate, as the timing window between end of the scan in and settling period and the end of the frame period becomes narrow, as well as because the likelihood that the next frame period will be delayed increases with an increase in frame rate. Accordingly, in some embodiments, the current frame rate (signal **1508**) is utilized as one of the input parameters **1502** considered by the strobe positioning module **1500** in determining a suitable strobe position.

Sensitivity to screen tearing relative to sensitivity to latency, skipped frames, and judder often varies from user to user. For example, gamers often seek to minimize latency and accept the cost of more frequent screen tearing, whereas a casual viewer of a video often prefers to avoid screen tearing where possible at the cost of increased latency. Accordingly, user input **1510** (one embodiment of signal **912**, FIG. **9**) also is employed as an input parameter **1502** by the strobe positioning module **1500**. To illustrate, one user provides user input indicating that earlier activation of the illumination strobe is preferable to later activation of the illumination strobe in view of reducing latency, whereas another user provides user input indicating that later activation of the illumination strobe is preferable so as to mitigate screen tearing. Also, different displays have different transition times from the previous pixel to the current pixel value, ranging from under 1 ms to many ms, especially with LC displays, affecting the visibility of tearing for a particular strobe position. A user input, or parameters retrieved from the display or a database of displays, facilitate varying the strobe position to better suit the monitor characteristics.

The relationship between the values of the input parameters **1502** and the resulting strobe position (as indicated by representation **1504**) are represented at the rendering device **302** (or at the display device **304**) using any of a variety of structures or mechanisms. In some embodiments, the relationship is represented using one or more LUTs **1510** or other tables, with each entry of the LUT **1510** being indexed based on one or a combination of input parameters and the corresponding entry containing the representation **1504**, or a value upon which the representation **1504** is based. In other embodiments, the relationship between input parameter(s) **1502** and strobe positions(s) of an illumination configuration is provided by one or more functions **1512** or other functional algorithms implemented in software code and executed as part of, for example, the graphics driver **710** at the rendering device **302** or executed at the display controller **316** of the display device **304**.

In yet other embodiments, the relationship between input parameter(s) **1502** and strobe positions for an illumination configuration is provided using a learned model **1514** developed using a neural network or other ML algorithm, which incorporates a history of some or all of the input parameters **1502** to train and refine the learned model **1514**. To illustrate, in a variable frame rate implementation, the ML algorithm monitors a history **1516** of previous frame periods, including their starts and whether they started early, late, or on time, and correlate this information with various operating parameters, including GPU loading, power states, identification of the video content application **704** being executed, sharing of resources among various guests, and the like, and from this training input develop a learned model **1514** that estimates the start time of the next frame period based on the current operational parameters received. With the next frame start time predicted and with an understanding of the frame rate and other considerations, the learned model **926** then can provide a strobe position that avoids activating after the next frame start time while also seeking to avoid activating during the scan in and settle period.

The LUT(s) **1510**, function(s) **1512**, or learned model **1514** used to define the relationship between one or more operational parameters **1502** and corresponding strobe positions of the illumination configuration can be configured in any of a variety of ways. For example, an OEM or other supplier can run extensive modeling, simulations, or other testing to determine a suitable strobe position of each of some or all possible combinations of values of the input parameters **1502**, and populate the one or more LUTs **1510** or configure the one or more functions **1512** accordingly. Further, in some embodiments, user input can be used to originally populate the one or more LUTs **1510** or configure the one or more functions **1512**, or to adjust previously-determined settings represented by the one or more LUTs **1510** or one or more functions **1512**. Still further, as explained above, the relationship in some instances is a dynamic relationship as represented by, for example, the learned model **1514** that is continuously updated based on various training inputs, including the input parameters **1502** themselves.

As noted above, a user can provide user input that operates to either define some aspect of the relationship between various values one or input parameters and corresponding values for one or more parameters of an illumination configuration, including strobe positioning, strobe illumination level, strobe duration, and one or both of front and back fill levels. This input, in one embodiment, can be received via one or more GUIs presented to the user, such as the GUI **720** implemented by the graphics driver **710** at the rendering device (e.g., as a configuration GUI for the corresponding GPU **308**) or the GUI **724** implemented at the display device **304** (e.g., as an on-screen display (OSD)). Alternatively, in one embodiment the GUI **724** is present on a local connected device such as a phone, or a completely remote location such as used for controlling a public billboard or movie theatre from a distant location. FIG. **16** illustrates an example GUI **1600** implemented as either GUI **720** or GUI **724** in accordance with some embodiments. The GUI **1600** typically includes one or more panels to graphically represent the relationships between input parameters and corresponding parameters of the illumination configuration, as well as one or more panels that implement input mechanisms to receive user input to set or adjust the illustrated relationships in a corresponding manner. As an example, the GUI **1600** can include a relationship panel **1602** that displays a chart **1604** that illustrates the current relationships between frame rate, the strobe illumination level, and the front and back fill levels. The relationship panel **1602** further can display a timing chart **1606** that illustrates the current setup for strobe positioning and strobe duration relative to the timing of the frame period, including the timing of the frame scan in and setup phase. Correspondingly, in this example the GUI **1600** includes an input panel **1608** that is to receive user input that sets or modifies one or more of the relationship parameters represented in chart **1604** or timing chart **1606**. One example includes input fields **1610** and **1612** to receive user input setting or modifying the minimum illumination level (F_FILL_MIN) and maximum illumination level (F_FILL_MAX), respectively, for the front fill level of a resulting illumination configuration, as well as input fields **1614** and **1616** to receive user input setting or modifying the minimum illumination level (B_FILL_MIN) and maximum illumination level (B_FILL_MAX), respectively, for the back fill level of the resulting illumination configuration.

Similarly, the input panel **1608** can include input fields to configure one or more parameters of an illumination strobe. To illustrate, in the depicted example the relationship between strobe illumination level and frame rate is represented as a piecewise linear relationship (line **1618**) with inflection points at frame rate **S0** (which controls when use of an illumination strobe starts), at frame rate **S1**, and at frame rate **S2** (which controls when the illumination strobe reaches its maximum illumination level). Accordingly, the input panel **1608** can include input fields **1620** and **1622** to receive user input setting or modifying the minimum illumination level (STROBE_MIN) and maximum illumination level (STROBE_MAX), respectively, of the illumination strobe, as well as input fields **1624**, **1626**, **1268**, **1630**, **1632**, and **1634** to receive user input setting or modifying the particular frame rate values for the inflection points **S0**, **S1**, **S2**, as well as the strobe illumination level to be used at each of the inflection points. The input panel **1608** further can facilitate configuration of the strobe positioning through input fields **1636** or **1638** or strobe duration through input fields **1640** or **1642**.

The input fields of the input panel **1608** can be implemented as fill-in fields, pull-down fields, and the like. In some instances, an absolute value is input to an input field. For example, the fields **1610**, **1612**, **1614**, **1616** each receives a value falling within a specified range, where the value input directly represents the corresponding illumination level. As another example, the fields **1636** and **1640** controlling strobe positioning and strobe duration, respectively, receive values representing a value in milliseconds. In other instances, a relative value is input to an input field. For example, input fields **1636**, **1638** can receive values that represent percentages of the duration of frame period, and thus are relative to the particular frame period at issue. Still further, rather than set a particular fixed value, the input panel **1608** can provide the ability for a user to specify an adjustment to a value that is dynamically determined by the display system **300**. To illustrate, in some implementations the relationship between GPU loading, frame rate, and starting position of an illumination strobe is dynamic and frequently updated by a learned model. One user finds that the learned model results in a relationship that causes the illumination strobe to occur somewhat early in the frame period and thus trigger screen tearing instances more frequently than the user would otherwise prefer. Accordingly, the user provides an adjustment value in the input field **1644** that adds a static adjustment to whatever strobe position value is otherwise determined by the strobe positioning module **1500** (FIG. **15**). For example, input of a value of −0.4 causes the strobe positioning module **1500** to shift the strobe position back by 0.4 milliseconds from the strobe position it otherwise would implement in the absence of the user input in order to accommodate the user.

Moreover, rather than, or in addition to, using input fields to obtain user input, in some embodiments one or more of the illustrated relationships are user manipulable via a mouse cursor, touchscreen, or other input mechanism so as to allow the user to graphically manipulate depicted graph or chart so as to achieve a desired relationship. For example, the inflection point S1 can be a graphical feature that the user can move along the abscissa and ordinate of the chart **1604** via a mouse cursor or touchscreen so as to change one or both of the frame rate value and the strobe illumination level associated with the inflection point.

In addition to obtaining user input from a user of the display system **300** to define or modify the relationships between various input parameters and parameters of an illumination configuration to be implemented for one or more frames, in some embodiments relationships defined by other users of other display systems are used to set or modify the relationships implemented by the display system **300**. FIG. **17** illustrates an example distributed system **1700** for providing such distributed relationship settings for an illumination configuration. The distributed system **1700** includes a remote server **1702** to which the display system **300** is connected via a network **1703** (e.g., a wireless local area network (WLAN), the Internet, etc.), as are one or more remote display systems, such as remote display systems **1704-1**, **1704-2**, **1704-3**. Each of the remote display systems **1704** operate to generate and display sequences of frames, and utilize the techniques described herein to set illumination configurations for the display of the frames of these sequences.

In the course of operation, each remote display system **1704** sends an illumination configuration update **1706** to the remote server **1702**. The illumination configuration update **1706** includes a representation of a relationship between one or more input parameters and one or more input configuration parameters as determined by the sending remote display system **1704** in its course of operation. This takes the form of, for example, one or more LUTs or other tables, descriptions of one or more software functions, a copy of a learned model, and the like. The illumination configuration update **1706** also includes information pertaining to the status of the remote display system **1704** itself at the time of generation of the relationship. This status information includes, for example, a serial number or model number of a component of the remote display system **1704**, an identifier of the video content application serving as the source of the frames associated with the illumination configuration update **1706**, representations of one or more hardware specifications or operational status (e.g., GPU loading) of the remote display system **1704**, and the like.

The remote server **1702** receives the periodic illumination configuration updates **1706** from each of the remote display systems **1704** and integrates them into one or more remotely-trained illumination configuration relationships that represents a consensus or merging between various input parameters and the parameters for an output configuration that should result based on multiple systems' experiences. These remotely-trained illumination configurations then are categorized or indexed at the remote server **1702** using any of a variety of indicia, including hardware setup indicia, model indicia, identifiers of the particular video content application associated with the relationship and the like.

When preparing to execute the video content application **704**, the display system **300** queries the remote server **1702** by sending an illumination configuration request **1708** to the remote server **1702**. The illumination configuration request **1708** includes identifiers of various relevant parameters of the display system **300**, such as serial number, model number, hardware specifications, identifier of the video content application **704**, current GPU loading, user preferences, and the like. In response, the remote server **1702** identifies a suitable remotely-trained illumination configuration relationship **1710** that most closely matches the relevant parameters provided in the illumination configuration request **1708** and transmits the identified remotely-trained illumination configuration relationship **1710** to the display system **300** for implementation. As with the illumination configuration updates **1706**, the remotely-trained illumination configuration relationship **1710** is represented by, for example, one or more LUTs, one or more software functions, one or more learned models, and the like.

As an example, the display system **300** could include a gaming console set to execute a particular video game (one embodiment of the video content application **704**). The display system **300** thus sends an illumination configuration request **1708** that identifies the model of the gaming console and the particular video game about to be played. The remote server **1702** then identifies a remotely-trained illumination configuration relationship **1710** created as the result of feedback from one or more of the remote display systems **1704** that are of the same or similar gaming console executing the same or similar video game application, and thus allowing the display system **300** to rapidly tailor the illumination configuration for displaying the frames generated by the video game application to settings found useful by other players on other similar display systems without training or further user input.

Turning now to FIGS. **18-26**, example implementations of the regional illumination control techniques **206** for display region-by-region illumination configuration control are described in greater detail. As noted above, these techniques employ a display device capable of individual illumination control on a per-region basis, where each illumination region is, for example, a subset of columns of the pixel array of the display device, a subset of rows of the pixel array, or a block of pixels that represents pixels at the intersection of a subset of one or more columns and a subset of one or more rows. These regional illumination control techniques **206** are employed separately, or in combination with each other, as well as in combination with one or more frame rate-based illumination control technique **202** or strobe position control technique **204** described above.

FIGS. **18** and **19** together illustrate an implementation of the brightness-based regional illumination control technique **212** for controlling the illumination configuration for a given illumination region based on an evaluation of a brightness of a region of the frame corresponding to the illumination region. The method **1800** of FIG. **18** illustrates the general flow of this technique in accordance with some embodiments, and is described with reference to the example implementation represented in FIG. **19** in which the source-side illumination control module **714** (FIG. 7) is responsible for determining the illumination configuration settings to be implemented by the display device **304**. However, the process described below can be adapted for implementation by the display-side illumination control module **718** using the guidelines provided herein.

At block **1802**, the GPU **308** renders or otherwise generates a frame **1902** in a sequence of frames at the direction of the video content application **704** and buffers the generated frame in a frame buffer **1904** at the rendering device **302**. At block **1804**, the display driver **712** then transmits the buffered pixel data and metadata representative of the generated frame **1902** on a row-by-row basis to the display device **304** via the interconnect **305**.

Concurrent with the frame generation and transmission processes of blocks **1802** and **1804**, the illumination control module **714** of the graphics driver **710** initiates the process of determining an illumination configuration for each illumination region of the display matrix **318**. In the example of FIG. **19**, the display matrix **318** is configured as a grid-based regional partitioning, having nine illumination regions **1906-1** to **1906-9**. However, while a nine-region example is illustrated, it will be appreciated that the display matrix **318** can be segmented into more or fewer regions. In some instances, each pixel is represented as its own separate region, with each individual color element, or sub-pixel, analyzed for blur and flicker and illuminated separately. Accordingly, at block **1806** the illumination control module **714** selects an illumination region and determines a brightness representation for the region of the frame corresponding to the selected illumination region (this region of the frame referred to herein as the "frame region"). To illustrate, in some embodiments, the graphics driver **710** tasks the GPU **308** with generating a histogram **1812** for the frame region, with the histogram **1812** indicating the number of pixels within the frame region having a corresponding pixel value, or falling within a corresponding pixel value range or "bucket." The illumination control module **714** then determines the brightness representation for the frame region based on the histogram **1812**. For example, the brightness representation indicates the number or proportion of pixels having a pixel value greater than a threshold pixel value, an average pixel value for the pixels in the histogram **812**, and the like. In other embodiments, the graphics driver **710** tasks the GPU **308** with generating an average brightness value **1814** for the frame region (e.g., akin to an average picture level (APL), but for that particular frame region rather than the entire frame), and the brightness representation for the frame region thus includes, or is based on, this average brightness value. Note that, in some embodiments, the brightness representation is determined based on, the white luminance level, whereas in other embodiments a separate brightness representation is determined for each of the individual sub-colors and luminance. For ease of illustration, calculation of the brightness representation based on the white luminance level is utilized in the descriptions and examples below.

At block **1808**, the illumination control module **714** either determines an illumination configuration for the illumination region or modifies an illumination configuration previously identified for the illumination region based on the brightness representation of the region. To illustrate, in some embodiments, the illumination control module **714** determines a default illumination configuration for the frame using one or a combination of the techniques described above, and then the illumination control module **714** modifies the default illumination configuration for each illumination region based on the brightness representation of the corresponding frame region to generate a particular region-specific illumination configuration. For example, as described below, the brightness representation can be used to increase the strobe output and decrease a fill output from their default levels, or conversely decrease the strobe output and increase a fill output from their default levels. In other embodiments, the brightness representation is used to select a particular illumination configuration from a set of predefined illumination configurations for use for that region.

The relationship between the brightness representation of a frame region and corresponding illumination configuration for an illumination region (or modification to a default illumination configuration on a per-region basis) in one embodiment is implemented using one or more LUTs **1816**, one or more software functions **1818**, or a learned model **1820** developed by an ML algorithm trained on previous use and previous user input on various settings. For example, a LUT **1816** has a plurality of entries indexed based on a corresponding brightness representation, or corresponding range of brightness representations, and with each corresponding entry storing a representation of a corresponding illumination configuration, including values for parameters such the particular front illumination fill level, back illumination fill level, strobe level, strobe position, strobe duration, and the like. As another example, a default frame-wide illumination configuration is specified, and each entry of the LUT **1816** includes an indication of a particular modification to the default illumination configuration, such as specifying an amount by which the strobe level is to be decreased from the default strobe level and an amount by which the fill level is to be increased form the default strobe level. As the flicker caused by an illumination strobe typically is more noticeable at brighter pixel levels and less noticeable at darker pixel levels, in at least one embodiment, the relationship between brightness representation and the corresponding region-specific illumination configuration is one that causes illumination strobe to be deemphasized and fill level to be emphasized in brighter frame regions and, conversely, causes illumination strobe to be emphasized and fill level to be deemphasized in darker frame regions. To illustrate, for a first frame region having a brightness representation above a high threshold and thus indicating the first frame region has a high average brightness, the illumination control module **714** in this example implements a constant level fill illumination configuration for the illumination region associated with the first frame region, whereas for a second frame region having a brightness representation below a low threshold and thus indicating the second frame region has a low average brightness, the illumination control module **714** in this example implements a strobe-only illumination configuration for the illumination region associated with the second frame region. However, for a third frame region having a brightness representation between the low and high thresholds, the illumination control module **714** linearly or non-linearly adjusts a strobe output and a fill output in opposite directions based on the brightness representation so that the strobe output is emphasized and the fill output deemphasized as average brightness increases within this range.

The illumination control module **714** repeats the process of blocks **1806** and **1808** for each illumination region of the display matrix **318** so as to determine a region-based illumination configuration (or region-based illumination configuration modification) for each illumination region, and transmits a representation **1908** of the illumination configuration, or illumination configuration modification, for each illumination region to the illumination control module **718** implemented at the display controller **316** of the display device **304**. For example, the representation **1908** can include a data structure having an entry for each of illumination regions **1906-1** to **1906-9**, with each entry storing values for the various parameters of the illumination configuration to be implemented for that illumination region. Alternatively, the data structure includes an entry representing a general illumination configuration, and each region-associated entry includes data indicating how the general illumination configuration is to be modified to create a regions-specific illumination configuration for that region.

At block **1822**, the display device **304** proceeds with display of the frame **1902** during its corresponding frame period. As part of this process, the illumination control module **718** controls, via the display controller **316**, the illumination at each illumination region of the display matrix **318** during the frame period for the frame **1902** so as to implement the illumination configuration for that illumination region as specified in the per-region representation **1908**. In other embodiments, the illumination control module **714** transmits one or more data structures with values representing the brightness representation for each frame region, and it is the illumination control module **718** that determines or modifies an illumination configuration for each illumination region based on the received brightness representation for that region. In yet other embodiments, rather than receive the brightness representations from the rendering device **302**, the illumination control module **718** of the display device **304** determines the brightness representations for each frame region (e.g., by generating a histogram or other per-region brightness representation) at the display device **304**, and then determining a per-region illumination configuration based on the locally-determined per-region brightness representations.

FIGS. **20-22** together illustrate an implementation of the motion-based regional illumination control technique **214** for controlling the illumination configuration for a given illumination region based on an estimation of motion in the corresponding frame region. The method **2000** of FIG. **20** illustrates the general flow of this technique in accordance with some embodiments, and is described with reference to the example implementation represented in FIG. **21** in which the source-side illumination control module **714** (FIG. **7**) is responsible for determining the illumination configuration settings to be implemented by the display device **304**. However, the process described below can be adapted for implementation by the display-side illumination control module **718** using the guidelines provided herein.

At block **2002**, the GPU **308** renders or otherwise generates a frame **2102** in a sequence of frames at the direction of the video content application **704** and buffers the generated frame in a frame buffer **2104** at the rendering device **302**. At block **2004**, the display driver **712** then transmits the buffered pixel data and metadata representative of the generated frame **2102** on a row-by-row basis to the display device **304** via the interconnect **305**.

Concurrent with the frame generation and transmission processes of blocks **2002** and **2004**, the illumination control module **714** of the graphics driver **710** initiates the process of determining an illumination configuration for each illumination region of the display matrix **318** based on motion estimations for each corresponding frame region. In the example of FIG. **21**, the display matrix **318** is configured as a grid-based regional partitioning, having nine illumination regions **2106-1** to **2106-9**. Accordingly, at block **2006** the illumination control module **714** selects a region of the current frame and determines motion estimation region representation for the frame region corresponding to the selected region.

As is well understood in the art, motion estimation is a process of determining the transformation of a previous frame into the current frame. Typically, motion estimation reflects a comparison of the current frame to the preceding frame or other previous reference frame, and determining motion vectors that represent the movement of objects or pixel blocks from their positions in the reference frame to their positions in the current frame. The GPU **308** can use any of a variety of well-known or proprietary techniques to determine the motion vectors representing the motion for the current frame, including Full Search and other block-matching techniques, phase-correlation techniques, frequency-matching techniques, pixel recursive techniques, and optical flow techniques. From the motion vectors determined for the frame, the GPU **308** or other component of the rendering device **302** then determines a motion estimate representation for each of the frame regions corresponding to illumination regions **2106-1** to **2106-9** based on the motion vectors that have an origin in the subject region of the current frame, on the motion vectors that have a destination in the subject region of the current frame, or a combination thereof. To illustrate, in one embodiment, the GPU **308** tallies the number of macroblocks or coding tree units (CTUs) in the frame region that have a motion vector (or a motion vector above a certain magnitude threshold to filter jitter) and then determines a motion estimate representation for this frame region based on this number. As another example, in another embodiment the GPU **308** generates an average motion vector magnitude or other statistical evaluation from the motion vectors of the macroblocks or CTUs in the frame region and generate the motion estimation representation for this frame region based on this statistical evaluation.

At block **2008**, the illumination control module **714** either determines an illumination configuration for the illumination region or modifies an illumination configuration previously identified for the region based on the motion estimate representation of the corresponding frame region. To illustrate, in some embodiments, the illumination control module **714** determines a default illumination configuration for the frame using one or a combination of the techniques described above, and then the illumination control module **714** modifies the default illumination configuration for each illumination region based on the motion estimate representation of the frame region to generate a particular region-specific illumination configuration. In other embodiments, the motion estimation representation is used to select a particular illumination configuration from a set of predefined illumination configurations for use for that region.

The relationship between the motion estimation representation for a frame region and corresponding illumination configuration for a corresponding illumination region (or modification to a default illumination configuration on a per-region basis) can be implemented using one or more LUTs **2016**, one or more software functions **2018**, or a learned model **2020** developed by an ML algorithm trained on previous use and previous user input on various settings. For example, a LUT **2016** has a plurality of entries indexed based on a corresponding motion estimation representation, or corresponding range of motion estimation representations, and with each corresponding entry storing a representation of a corresponding illumination configuration, including values for parameters such the particular front illumination fill level, back illumination fill level, strobe level, strobe position, strobe duration, and the like. As another example, a default frame-wide illumination configuration is specified, and each entry of the LUT **2016** includes an indication of a particular modification to the default illumination configuration, such as specifying an amount by which the strobe level is to be decreased from the default strobe level and an amount by which the fill level is to be increased form the default strobe level.

With regard to the relationship between motion estimation for a frame region and illumination configuration control, it is noted that frame regions having relatively low motion are less likely to suffer from motion blur, and thus implementation of a pronounced illumination strobe for the corresponding illumination region is likely unnecessary for motion blur mitigation, but could introduce flicker depending on the frame rate without any benefit. Conversely, frame regions having relatively high motion are likely to exhibit motion blur, and for such regions an illumination strobe is emphasized. Accordingly, in at least one embodiment, the relationship implemented by the illumination control module **714** to set or modify an illumination configuration for the illumination region generally provides for increasing strobe emphasis and decreasing fill emphasis with an increase in motion estimation, and conversely, for decreasing strobe emphasis and increasing fill emphasis with a decrease in motion estimation for the frame region. Thus, for a scheme in which a frame-wide default or general illumination configuration is modified on a region-by-region basis, the illumination control module **714** can use the motion estimate representation to decrease the strobe output and increase a fill output from their default levels for a frame region identified as containing relatively little motion, or conversely increase the strobe output and decrease a fill output from their default levels for a region identified as containing relatively high motion. To illustrate, for a first frame region having a motion estimation representation below a low threshold and thus indicating the first frame region has a very low or zero motion estimation, the illumination control module **714** in one embodiment implements a constant level fill illumination configuration for the illumination region corresponding to the first frame region, whereas for a second frame region having a motion estimation representation above a high threshold and thus indicating the second frame region has a very high motion estimation, the illumination control module **714** in one embodiment implements a strobe-only illumination configuration for the illumination region corresponding to the second frame region. However, for a third frame region having a motion estimation representation between the low and high thresholds, the illumination control module **714** linearly or non-linearly adjusts one or both of a strobe level and duration and a fill level in opposite directions based on the motion estimation representation so that the strobe output is emphasized and the fill output deemphasized as motion estimation increases within this range.

The illumination control module **714** repeats the process of blocks **2006** and **2008** for each frame region of the frame corresponding to an illumination region of the display matrix **318** so as to determine a region-based illumination configuration (or region-based illumination configuration modification) for each illumination region, and transmits a representation **2108** of the illumination configuration, or illumination configuration modification, for each illumination region to the illumination control module **718** implemented at the display controller **316** of the display device **304**. As similarly described above, the representation **2108** can include a data structure having an entry for each of illumination regions **2106-1** to **2106-9**, with each entry storing values for the various parameters of the illumination configuration to be implemented for that illumination region. Alternatively, the data structure includes an entry representing a general illumination configuration, and each region-associated entry includes data indicating how the general illumination configuration is to be modified to create a regions-specific illumination configuration for that illumination region.

At block **2022**, the display device **304** proceed with display of the frame **2102** during its corresponding frame period. As part of this process, the illumination control module **718** controls, via the display controller **316**, the illumination at each illumination region of the display matrix **318** during the frame period for the frame **2102** so as to implement the illumination configuration for that illumination region as specified in the per-region representation **2108**. In other embodiments, the illumination control module **714** transmits one or more data structures with values representing the motion estimation representation for each illumination region, and it is the illumination control module **718** that determines or modifies an illumination configuration for each illumination region based on the received motion estimation representation for that region.

To illustrate an example of the method **2000**, FIG. **22** depicts an example sequence **2200** of two frames **2202-1** and **2202-2**, with frame **2202-1** preceding frame **2202-2** in display order. Each of the frames **2202-1** and **2202-2** is partitioned into a 3×3 grid of frame regions, with each frame region corresponding to an independently-controlled illumination region of the display matrix **318**. In this example, the sequence **2200** represents motion of pixel content representing an automobile object **2204** as it travels horizontally, with the bulk of the pixel content originating in a region **2206** of frame **2202-1** and appearing in a frame region **2208** of frame **2202-2**. Assume, for this example, that there is no other motion of significance in the sequence. Thus, for frame **2202-2**, frame regions **2206** and **2208** exhibit considerable motion from the preceding frame **2202-1**, and thus frame regions **2206** and **2208** for frame **2202-2** would be assigned motion estimate representations with high values representing considerable motion, whereas the remaining frame regions of the frame **2202-2** would be assigned motion estimate representations with low values representing low or zero motion. Accordingly, for each of frame regions **2206** and **2208**, the illumination control module **714** would generate a region-specific illumination configuration that provides a prominent illumination strobe and deemphasized illumination fill (including no illumination fill) so as to mitigate the motion blur that otherwise potentially would occur in the two corresponding illumination regions with a less emphasized illumination strobe. For frame regions **2210** and **2210** that contain a slight amount of motion and thus are represented by small, non-zero motion estimate representations, the illumination control module **714** would generate a region-specific illumination configuration that balances the strobe output and the fill output based on the motion estimation representation for the frame region so as to balance the risk of motion blur versus flicker in the associated illumination region. For each of the remaining regions, the illumination module **714** would generate a region-specific illumination configuration that provides a prominent illumination fill and deemphasized illumination strobe (including no strobe, or a constant-level fill illumination) so as to mitigate the flicker that otherwise potentially would occur in these illumination regions if a more prominent strobe were to be used.

FIGS. **23-26** together illustrate an implementation of the foveated regional illumination control technique **216** for controlling the illumination configuration for a given illumination region based on whether the illumination region is a foveal region or a peripheral region. In order to implement such a technique, the display system **300** utilizes a gaze tracking subsystem **2300** for determining the current gaze position of a user, as illustrated by FIG. **23**. In at least one embodiment, the gaze tracking subsystem **2300** utilizes one or more light sources **2302** (e.g., infrared (IR) LEDs) co-located with the display matrix **318** of the display device **304** to illuminate one or both eyes **2304** of a user, as well as one or more imaging cameras **2306** directed toward the position of the eyes **2304** so as to capture imagery of the user's eyes **2304** as illuminated by the light sources **2302**. A gaze tracking module **2308** analyzes the captured imagery to determine a current gaze direction **2310** of the eyes **2304** using any of a variety of well-known or proprietary gaze tracking techniques, and from a known geometrical configuration between the position of the imaging camera **2306**, the position of the display matrix **318**, the position of the user's eyes **2304**, and the gaze direction **2310**, triangulates the current gaze position **2312**; that is, the point on the display matrix **318** that is the target of the user's current foveal view. The gaze tracking module **2308** then provides a gaze position representation **2314** of the current gaze position **2312** to the graphics driver **710**, the GPU **308**, or other component of the rendering device **302**. The gaze position representation **2314** can include, for example, an (X,Y) coordinate pair identifying the (X,Y) position of the current gaze position **2312** relative to the pixels of the display matrix **318**, a value identifying the illumination region of the display matrix **318** that contains the location of the current gaze position **2312**, and the like.

Turning now to FIG. **24**, the method **2400** of FIG. **24** illustrates the general flow of the foveated regional illumination control technique **216** in accordance with some embodiments, and is described with reference to the example implementation represented in FIG. **25** in which the source-side illumination control module **714** (FIG. **7**) is responsible for determining the illumination configuration settings to be implemented by the display device **304**. However, the process described below can be adapted for implementation by the display-side illumination control module **718** using the guidelines provided herein.

At block **2402**, the GPU **308** renders or otherwise generates a frame **2502** in a sequence of frames at the direction of the video content application **704** and buffers the generated frame in a frame buffer **2504** at the rendering device **302**. At block **2404**, the display driver **712** then transmits the buffered pixel data and metadata representative of the generated frame **2502** on a row-by-row basis, a column-by-column basis, a block-by-block basis, or some other pattern basis, to the display device **304** via the interconnect **305**.

Concurrent with the frame generation and transmission processes of blocks **2402** and **2404**, the illumination control module **714** of the graphics driver **710** initiates the process of determining an illumination configuration for each illumination region of the display matrix **318** based on the current gaze position **2312** and its relationship to the illumination regions region. In the example of FIG. **25**, the display matrix **318** is configured as a grid-based regional partitioning, having a 5×5 arrangement of illumination regions **2501-1** to **2501-25**. At block **2406**, the gaze tracking subsystem **2300** determines the current gaze position **2312** and provides the corresponding gaze position representation **2314** to the illumination control module **714**. At block **2408**, the illumination control module **714** classifies each of the illumination regions **2501-1** to **2501-25** based on the location of the current gaze position **2312** represented by the gaze position representation **2314** relative to the illumination region at issue. In some embodiments, the illumination control module **714** implements a two tier approach in which each illumination region is classified as either a foveal region or a peripheral region based on distance of the region from the current gaze position **2312**. In this case, the illumination region containing the current gaze position **2312** is designated as the foveal region and all of the remaining illumination regions are designated as peripheral regions. In other embodiments, more than two tiers of classification are implemented based on distance from the current gaze position **2312**. For example, in one embodiment the illumination control module **714** implements a three tier approach in which the illumination region containing the current gaze position **2312** is classified as the foveal region, the illumination regions immediately adjacent to the foveal region are classified as intermediate regions, and the remaining illumination regions are classified as peripheral regions. Other classification schemes can be implemented using the guidelines provided herein.

At block **2410**, the illumination control module **714** either determines an illumination configuration for a selected illumination region or modifies an illumination configuration previously identified for the selected illumination region based on the classification of the selected region. To illustrate, in some embodiments, the illumination control module **714** determines a default illumination configuration for the frame using one or a combination of the techniques described above, and then the illumination control module **714** modifies the default illumination configuration for each illumination region based on the classification of the region to generate a particular region-specific illumination configuration. In other embodiments, the classification of the region is used to select a particular illumination configuration from a set of predefined illumination configurations for use for that region.

In at least one embodiment, the relationship between the gaze-based classification for an illumination region and corresponding illumination configuration for the illumination region (or modification to a default illumination configuration on a per-region basis) are implemented using one or more LUTs **2412**, one or more software functions **2414**, or a learned model **2416** developed by an ML algorithm trained on previous use and previous user input on various settings. For example, a LUT **2412** has a plurality of entries indexed based on a corresponding gaze-based classification, with each corresponding entry storing a representation of a corresponding illumination configuration, including values for parameters such the particular front illumination fill level, back illumination fill level, strobe level, strobe position, strobe duration, and the like. As another example, a default frame-wide illumination configuration is specified, and each entry of the LUT **2412** includes an indication of a particular modification to the default illumination configuration, such as specifying an amount by which the strobe level is to be decreased from the default strobe level and an amount by which the fill level is to be increased form the default strobe level.

In the human visual system, a user's peripheral vision typically is more susceptible to noticing flicker than the user's foveal vision. Conversely, reduced acuity in a user's peripheral vision typically causes the user to be less susceptible to noticing motion blur in the peripheral vision, and more likely to notice motion blur in the foveal vision. Accordingly, in at least one embodiment, the relationship implemented by the illumination control module **714** to set or modify an illumination configuration for the illumination region generally provides for increased strobe emphasis and decreased fill emphasis for an illumination region classified as a foveated region, and conversely, for decreased strobe emphasis and increased fill emphasis for illumination regions classified as peripheral regions. Further, in embodiments in which an intermediate region classification is utilized, the relationship provides for a balance between strobe output and fill output for regions identified as such. Thus, for a scheme in which a frame-wide default or general illumination configuration is modified on a region-by-region basis, the illumination control module **714** can use the gaze-based classification for the illumination region to decrease the strobe output and increase a fill output from their default levels for an illumination region identified as a peripheral region, or conversely increase the strobe output and decrease a fill output from their default levels for a region identified the foveal region. Further, for an illumination region classified as an intermediate region, the general illumination configuration is employed without modification in this example.

The illumination control module **714** repeats the process of block **2410** for each illumination region of the display matrix **318** so as to determine a region-based illumination configuration (or region-based illumination configuration modification) for each illumination region, and transmits a representation **2508** of the illumination configuration, or illumination configuration modification, for each illumination region to the illumination control module **718** implemented at the display controller **316** of the display device **304**. As similarly described above, the representation **2508** can include a data structure having an entry for each of illumination regions **2501-1** to **2501-25**, with each entry storing values for the various parameters of the illumination configuration to be implemented for that illumination region. Alternatively, the data structure includes an entry representing a general illumination configuration, and each region-associated entry includes data indicating how the general illumination configuration is to be modified to create a regions-specific illumination configuration for that illumination region.

At block **2418**, the display device **304** proceeds with display of the frame **2502** during its corresponding frame period. As part of this process, the illumination control module **718** controls, via the display controller **316**, the illumination at each illumination region of the display matrix **318** during the frame period for the frame **2502** so as to implement the illumination configuration for that illumination region as specified in the per-region representation **2508**. In other embodiments, the illumination control module **714** transmits one or more data structures with values representing the gaze-based classification for each illumination region, and it is the illumination control module **718** that determines or modifies an illumination configuration for each illumination region based on the received gaze-based classification for that region.

To illustrate an example of the method **2400**, FIG. **26** depicts two different frames **2602-1** and **2602-2**. Each of the frames **2602-1** and **2602-2** is partitioned into a 5×5 grid of frame regions, with each frame region corresponding to an independently-controlled illumination region **2501** of the display matrix **318**. Frame **2602-1** illustrates the two-tier classification approach described above. In this example, the current gaze position (identified by icon **2604**) is located in the area associated with illumination region **2501-17** (see FIG. **25**), and thus illumination region **2501-17** is classified as the foveal region and the remaining illumination regions **2501-1** to **2501-16** and **2501-18-2501-25** are classified as peripheral regions. Accordingly, the region-specific illumination configuration employed by the display device **304** for the illumination region **2501-17** would be set or modified to emphasize use of an illumination strobe and deemphasize use of illumination fill, and while the other illumination regions would have region-specific illumination configurations that would be set or modified to deemphasize strobe use and emphasize fill use.

Frame **2602-2** illustrates the two-tier classification approach also described above. In this example, the current gaze position (identified by icon **2604**) is located in the area associated with illumination region **2501-13** (see FIG. **25**), and thus illumination region **2501-13** is classified as the foveal region. Illumination regions **2501-7**, **2501-8**, **2501-9**, **2501-12**, **2501-14**, **2501-17**, **2501-18**, and **2501-19** are immediately adjacent to the illumination region **2501-13** and thus are classified as intermediate regions, and the remaining illumination regions are classified as peripheral regions. Accordingly, in this example, the region-specific illumination configuration employed by the display device **304** for the foveal region would be set or modified to emphasize use of an illumination strobe and deemphasize use of illumination fill, the region-specific illumination configurations for the peripheral regions would be set or modified to deemphasize strobe use and emphasize fill use, and the region-specific illumination configurations for the intermediate regions could, for example, default to a general frame-wide illumination configuration determined using one of the other illumination configuration control techniques described above.

In some embodiments, the apparatus and techniques described above are implemented in a system including one or more integrated circuit (IC) devices (also referred to as integrated circuit packages or microchips), such as one or more of the components of the display system **300** described above with reference to FIGS. **1-26**. Electronic design automation (EDA) and computer aided design (CAD) software tools typically are used in the design and fabrication of these IC devices. These design tools typically are represented as one or more software programs. The one or more software programs include code executable by a computer system to manipulate the computer system to operate on code representative of circuitry of one or more IC devices so as to perform at least a portion of a process to design or adapt a manufacturing system to fabricate the circuitry. This code can include instructions, data, or a combination of instructions and data. The software instructions representing a design tool or fabrication tool typically are stored in a computer readable storage medium accessible to the computing system. Likewise, the code representative of one or more phases of the design or fabrication of an IC device are stored in and accessed from the same computer readable storage medium or a different computer readable storage medium.

A computer readable storage medium includes any non-transitory storage medium, or combination of non-transitory storage media, accessible by a computer system during use to provide instructions and/or data to the computer system. Such storage media can include, but is not limited to, optical media (e.g., compact disc (CD), digital versatile disc (DVD), Blu-Ray disc), magnetic media (e.g., floppy disc, magnetic tape, or magnetic hard drive), volatile memory (e.g., random access memory (RAM) or cache), non-volatile memory (e.g., read-only memory (ROM) or Flash memory), or microelectromechanical systems (MEMS)-based storage media. The computer readable storage medium is, for example, embedded in the computing system (e.g., system RAM or ROM), fixedly attached to the computing system (e.g., a magnetic hard drive), removably attached to the computing system (e.g., an optical disc or Universal Serial Bus (USB)-based Flash memory), or coupled to the computer system via a wired or wireless network (e.g., network accessible storage (NAS)).

In some embodiments, certain aspects of the techniques described above are implemented by one or more processors of a processing system executing software. The software includes one or more sets of executable instructions stored or otherwise tangibly embodied on a non-transitory computer readable storage medium. The software can include the instructions and certain data that, when executed by the one or more processors, manipulate the one or more processors to perform one or more aspects of the techniques described above. The non-transitory computer readable storage medium can include, for example, a magnetic or optical disk storage device, solid state storage devices such as Flash memory, a cache, random access memory (RAM) or other non-volatile memory device or devices, and the like. The executable instructions stored on the non-transitory computer readable storage medium are implemented in source code, assembly language code, object code, or other instruction format that is interpreted or otherwise executable by one or more processors.

Note that not all of the activities or elements described above in the general description are required, that a portion of a specific activity or device may not be required, and that one or more further activities can be performed, or elements included, in addition to those described. Still further, the order in which activities are listed are not necessarily the order in which they are performed. Also, the concepts have been described with reference to specific embodiments. However, one of ordinary skill in the art appreciates that various modifications and changes can be made without departing from the scope of the present disclosure as set forth in the claims below. Accordingly, the specification and figures are to be regarded in an illustrative rather than a restrictive sense, and all such modifications are intended to be included within the scope of the present disclosure.

Benefits, other advantages, and solutions to problems have been described above with regard to specific embodiments. However, the benefits, advantages, solutions to problems, and any feature(s) that can cause any benefit, advantage, or solution to occur or become more pronounced are not to be construed as a critical, required, or essential feature of any or all the claims. Moreover, the particular embodiments disclosed above are illustrative only, as the disclosed subject matter can be modified and practiced in different but equivalent manners apparent to those skilled in the art having the benefit of the teachings herein. No limitations are intended to the details of construction or design herein shown, other than as described in the claims below. It is therefore evident that the particular embodiments disclosed above can be altered or modified and all such variations are considered within the scope of the disclosed subject matter. Accordingly, the protection sought herein is as set forth in the claims below.

What is claimed is:

1. A computer-implemented method comprising:

displaying a sequence of frames at display device using an illumination strobe during each frame period associated with a corresponding frame of the sequence of frames; and

determining a position of the illumination strobe within each frame period based at least in part on one or more current operational parameters representing a current loading of a rendering device used to generate the sequence of frames.

2. The computer-implemented method of claim **1**, wherein determining the position of the illumination strobe comprises determining a position of the illumination strobe so as to follow completion of a scan in and settling process for preparing a pixel matrix of the display device to display a frame and to precede a start of a next frame period.

3. The computer-implemented method of claim **1**, further comprising:

predicting a start of a next frame period based on at least one of a frame rate of the sequence of frames and an operational loading of the rendering device during generation of the sequence of frames.

4. The computer-implemented method of claim **1**, further comprising predicting a start of a next frame based on a learned model trained by a machine learning algorithm based on a history of operational characteristics associated with at least one previous sequence of frames.

5. The computer-implemented method of claim **1**, further comprising:

determining at least one of an illumination level of the illumination strobe, an illumination level of an illumination fill preceding the illumination strobe, and an illumination level of an illumination fill following the illumination strobe based on a frame rate of the sequence of frames.

6. The computer-implemented method of claim **1**, wherein determining the position of the illumination strobe is further based on one or more input parameters, the one or more input parameters including user input for modifying a setting for the position of the illumination strobe.

7. The computer-implemented method of claim **1**, wherein determining the position of the illumination strobe is further based on one or more input parameters, the one or more input parameters including an identifier of a video content application that sourced the sequence of frames.

8. The computer-implemented method of claim **1**, further comprising:

determining a position of the illumination strobe within each frame period based on a presence of a delayed vertical sync between a frame rate of the rendering device and a refresh rate of the display device.

9. A display system, configured to:

render, with a rendering device, a sequence of frames for display at a display device, wherein the display device is to use an illumination strobe during each frame period associated with a corresponding frame of the sequence of frames; and

determine a position of the illumination strobe within each frame period based at least in part on one or more current operational parameters representing a current loading of the rendering device.

10. The display system of claim **9**, wherein the display system is configured to determine the position of the illumination strobe by one of:

setting the position of the illumination strobe so as to occur following completion of a scan in and settling process for preparing a pixel matrix of the display device to display a frame and to precede a start of a next frame period; and

setting the position of the illumination strobe so as to occur following the start of the frame period and prior to completion of the scan in and settling process.

11. The display system of claim **9**, wherein the display system further is configured to:

predict a start of a next frame period based on at least one of a frame rate of the sequence of frames and an operational loading of the rendering device during generation of the sequence of frames.

12. The display system of claim **9**, wherein the display system is configured to predict a start of a next frame period based on a learned model trained by a machine learning algorithm based on a history of operational characteristics associated with at least one previous sequence of frames.

13. The display system of claim **9**, wherein to determine the position of the illumination strobe within each frame period is further based on one or more input parameters, and wherein the one or more input parameters include a frame rate of the sequence of frames.

14. The display system of claim **9**, wherein the display system further is configured to:

determine at least one of an illumination level of the illumination strobe, an illumination level of an illumination fill preceding the illumination strobe, and an illumination level of an illumination fill following the illumination strobe based on the frame rate.

15. The display system of claim **9**, wherein to determine the position of the illumination strobe within each frame period is further based on one or more input parameters, and wherein the one or more input parameters include user input for modifying a setting for the position of the illumination strobe.

16. The display system of claim **9**, wherein to determine the position of the illumination strobe within each frame period is further based on one or more input parameters, and wherein the one or more input parameters include an identifier of a video content application that sourced the sequence of frames.

17. The display system of claim **9**, further comprising:

the display device, wherein the display device is configured to receive a representation of an illumination configuration for the frame period and implement the illumination configuration during the frame period, and wherein the representation of the illumination configuration includes a representation of the position of the illumination strobe.

18. The display system of claim **17**, wherein the display device is a transmissive-type display device and the display device is configured to implement the illumination configuration via control of a backlight in accordance with the illumination configuration.

19. The display system of claim **17**, wherein the display device is an emissive-type display device and the display device is configured to implement the illumination configuration by adjusting power provided to pixels of the display device in accordance with the illumination configuration.

20. A display system comprising:

a display device configured to:

receive a sequence of frames for display from a rendering device;

employ an illumination strobe during each frame period associated with a corresponding frame of the sequence of frames; and

determine a position of the illumination strobe within each frame period based on one or more input parameters, each input parameter representing a corresponding operational characteristic of the rendering device, the corresponding operational characteristic representing a current loading of the rendering device.

* * * * *